Performance of Flowable Concrete in Underground Structures

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Case Report

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Abstract

Flowable concrete gives special combinations of uniformity, performance and consistency requirements that cannot be possible by traditional normal slump concrete. It is more superior concrete than the traditional concrete with high workability without segregation, bleeding, and is also suitable for use on structures with long distance pumping i.e., more than 120-meter length, for example, in NATM tunnels and cross-passages, and the concrete structure of the station box. Flowable concrete can flow itself without vibration or little bit vibration like surface tamping outer surface of the formwork for achieving a smooth surface finish after de-shuttering. The proportion of the mix is to be used in concrete, it must ensure a balance between deformability and stability. The behavior of concrete can be influenced by the properties of the selected item in the concrete, and the aspect ratio of the mixture. There is a need for the development of a methodology for the design of the flowable concrete mix. The paper presents an experimental procedure for the mix design of flowable concrete for grade M40 and implementation of the same mix at the cast in situ Base slab, Roof slab Rcc walls for underground metro stations, NATM tunnel & cross passages in Mumbai Metro Project, package -UGC-07. The test results for acceptance characteristics of M40 grade flowable concrete such as Slump flow test, compressive strength at the ages of 7, 28, and 56 days determined, and results are included here. Successful production of temperature control flowable concrete from batching plant, transportation, placement procedures, and proper planning of handling and execution of flowable concrete at the site are presented in this article.

1. Introduction

Rheological properties of flowable concrete or self-compacting concrete are advanced than traditional normal slump concrete and hardened properties of concrete is same as traditional normal slump concrete [1]. Flowable concrete is suitable for a fast rate of concrete placement, with faster construction times and ease of flow around dense reinforcement without vibration or little bit surface tamping to get better surface finish. It ensures good homogeneity, pumping ability, best surface finish, consistent concrete strength, and durability of the concrete structure. "The workability of concrete describes the flowability, mobility, and stability of fresh concrete.

Specific measurement limits of Slump, Slump flow, Flow table cannot be fixed and its totally depends on placing condition of site, however concrete should be homogenies, cohesive, no settlement and no bleeding in mix" [2]. The hardened concrete properties like compressive strength, flexural strength, split tensile, etc. Are specifically stricken by composition of concrete ingredients. In Mumbai region river sand is not available and therefore construction industries are totally depending on manufactured sand. In M-sand it is difficult to maintain required fractions of sieve sizes for getting appropriate zone of sand i.e., zone II as per IS383:2016 [3]. According to site requirements only flowable concrete was suitable due to long distance of pipe pumping and congested reinforcement in the structure. Hence flowable concrete was developed by conducting several numbers of concrete mix trials and concluded that trials were achieving standards requirements for flowability by slump flow, and sieve segregation resistance tests as per specification mentioned in European standard [4]. Chemical admixtures i.e., superplasticizers required for optimized the cementitious content and minimize the W/C ratio for production of flowable concrete [5]. Appropriate selection of supplementary cementitious materials such like GGBS, Ultrafine GGBS-Alccofine, Crystalline growth admixture etc. are also required for improving durability, decreasing permeability, surface finish ability and improving the overall hardened properties of concrete.

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2. Concrete Ingredients

2.1 Cement

OPC 53 Grade cement of M/s Ultratech is used. Physical & Chemical properties are as given in Tables 1 & 2.

2.2 GGBS

Ground granulated blast furnace slag (GGBS) of M/s JSW obtained from Pen, Raigad, Maharashtra, India. The physical and chemical properties of GGBS are given in the Table 1 and Table 2, respectively.

2.3 Ultrafine GGBS -Alccofine

Ultrafine GGBS commercially available as Alccofine-1203 is a low calcium silicate-based mineral additive which is generally used as a replacement of silica fume in high-performance concrete [6]. Alccofine 1203 is a slag based SCM having ultra-fineness with optimized particle size distribution [7].

Table 1
Physical Properties of Cement, GGBS and UGGBS-Alccofine 1203 [1]

Physical Properties	Cement (OPC-53)	GGBS	UGGBS-Alccofine 1203
W-M-Y	14-04-2021	14-04-2021	14-04-2021
Specific Gravity	3.13	2.9	2.92
Fineness(m ² /kg)	288.2	482.5	1200
Particle size, micron	-	-	1.6
D ₁₀			4.5
D ₅₀			9.2
D ₉₀			10.8
D ₉₅			
Normal consistency (%)	29.0%	-	-
Soundness (Autoclave) (%)	0.020	0.020	-
Setting time (min.)	130 215	-	-
Initial			
Final			
Strength (N/mm ²)	36.5 46 69		
3days			
7days			
28days			
Slag Activity Index, %	-	72.8	92.5
a) At & 7 days		85.4	108.4
b) At & 28 days			

Table 2
Chemical Properties of Cement, GGBS and UFGGBS-Alccofine 1203 [1]

Chemical Properties	Cement	GGBS	UGGBS-Alccofine 1203
Loss on ignition, % by mass	2.98	0.10	0.32
Glass content, % by mass	-	87.24	86.92
Magnesium Oxide (MgO)	1.76	0.17	7.56
Total Sulphur (SO ₃), % by mass	2.9	0.25	0.22
Insoluble residue, % by mass	0.93	-	-
Alkali Content, % by mass	0.22	0.2	0.22
Total Chloride content, % by mass	0.017	0.011	0.015

Ordinary Portland Cement OPC-53 grade, GGBS and UGGBS-Alccofine are conformed to Indian Standard Specifications IS: 269–2015, IS 16714-2018 and IS 16715 – 2018 [8], [9] [10]

2.4 Chemical admixtures and crystalline growth waterproofing admixture

“Poly carboxylic ether-based superplasticizer admixture brand name Sika ViscoCrete 5138 & Sika ViscoCrete 5229NS M/s Sika are used to bring out the required water reduction and maintain the dispersing effect during time required for transportation and placement at site.

Crystalline growth waterproofing admixture brand name SIKI 101 H of M/s Sika. The use of crystalline admixtures (CA) has a potential of improving the durability and reducing permeability of concrete structures especially those exposed to environments like extradosed structure of underground

Table 3
Physical Properties of Chemical admixtures [1]

Characteristics	Product Name- Sika ViscoCrete 5138	Product Name-Sika ViscoCrete 5229NS
Specific gravity	1.125	1.115
pH	6.43	6.69
Dry material content	42.49	38.45
Chloride (as Cl), % by Mass	< 0.01	< 0.01

Table 4
Physical Properties of Crystalline Waterproofing admixture (C.W.A)

Characteristics	C.W.A-Product Name Sika 101 H
Appearance	Gray Powder
Density (kg/lit)	1.3
Dosage (%) by mass of cement	0.8-1
Permeability to water vapor at 3 bar pressures	Impermeable
Initial set time at 30 deg temperature	40 minutes

Concrete admixtures are conformed to Indian Standard Specifications I S: 9103:1999 [12] and Crystalline Waterproofing admixture confirmed to manufacturer technical product data sheet.

2.5 Aggregates

In Mumbai region, Maharashtra, India, river sand is not available and therefore construction industries are totally depending on manufactured sand.

Coarse aggregate and Manufactured sand are obtained from nearest source i.e., Kunde vahal, Panvel,,Raigargh, Maharashtra. Fine aggregate- M/sand and coarse aggregate are conformed to Indian Standard Specifications IS: 383–2016 [3].

Table 5 shows the physical properties of the coarse and fine aggregates.

Table 5
Physical Properties of Coarse and Fine Aggregates [1]

Physical tests	Coarse aggregate	Fine aggregate M-sand
Specific gravity	2.78	2.72
Water Absorption (%)	1.89	2.91
Bulk density (kg/m3)	1470	1730

3 Concrete Mix Compositions

The concrete mix is designed as per absolute volume method according to the Indian standard -Concrete mix proportioning Guidelines [13] to meet environmental exposure condition of Mumbai city, Maharashtra i.e., considered sever condition. The properties of the concrete ingredients differ from one state to another state of the same country, and it is totally depending on actual environmental exposer condition of site and quality of available concrete ingredients for making suitable concrete mix [14].

Concrete mix compositions are presented in Table 6 & Table No-7.

Table 6
Concrete Mix Proportions for Tunnel NATM Lining concrete M40 Grade [1].

<i>Sr. No.</i>	<i>Mix</i>	<i>Cement (Kg/m3)</i>	<i>GGBS (Kg/m3)</i>	<i>UGGBS (Kg/m3)</i>	<i>Powder (Kg/m3)</i>	<i>W/P Ratio</i>	<i>C.A (Kg/m3)</i>	<i>F.A M-Sand (Kg/m3)</i>	<i>C.A /FA ratio (%)</i>	<i>Water (Kg/m3)</i>	<i>Superplasticizer- Sika ViscoCrete 5138 (Kg/m3)</i>
1	TR1	330	150	20	500	0.3	999	883	53/47	150	9.0
2	TR2	350	150	20	520	0.317	930	851	52/48	165	7.02
3	TR3	360	160	20	540	0.309	1029	773	57/43	167	8.1
4	TR4	360	160	20	540	0.296	927	848	52/48	160	8.64
5	TR5	330	200	20	550	0.32	778	981	44/56	176	7.7

Five concrete mix design trials were taken of M40 Grade and finalized TR 5 for NATM Lining flowable concrete for implementing in NATM tunnel and Cross passages of underground Mumbai Metro Project in Package- UGC-07, Line – 3. Coarse aggregate content, fine aggregate content and cementitious content were optimized, until a slump flow of 500–700 mm is achieved by slump flow test. For each trial, tests are carried out in order that the trial mix satisfies slump flow test, T500, V-funnel and Sieve segregation resistance tests.

Table 7
Concrete Mix Proportions for the structures -Base slab, RCC walls and Roof slab Flowable Concrete M40 Grade [1].

<i>Sr. No.</i>	<i>Mix</i>	<i>Cement (Kg/m3)</i>	<i>GGBS (Kg/m3)</i>	<i>UGGBS (Kg/m3)</i>	<i>Powder (Kg/m3)</i>	<i>W/P Ratio</i>	<i>C.A (Kg/m3)</i>	<i>F.A M-Sand (Kg/m3)</i>	<i>C.A /FA ratio (%)</i>	<i>Water (Kg/m3)</i>	<i>Superplasticizer- Sika ViscoCrete 5229 NS (Kg/m3)</i>	<i>C.W.A (Kg/m3)</i>
1	TR6	315	145	20	480	0.313	1049	816	56/44	150	7.2	4.8
2	TR7	260	200	20	480	0.304	1064	814	56/44	146	6.72	4.8
3	TR8	260	200	20	480	0.313	1035	810	56/44	150	6.24	4.8
4	TR9	245	200	15	460	0.35	988	889	53/47	161	5.98	4.6

Four concrete mix design trials were taken for the structures -Base slab, RCC walls and Roof slab Flowable Concrete M40 Grade for metro Station in UGC-07 of Mumbai Metro Project, Line – 3. Satisfactory results obtained in trial mix no-TR 9. Coarse aggregate content, fine aggregate content and cementitious content were optimized, until a slump flow of 500–700 mm is achieved by slump flow test. For each trial, tests are carried out in order that the trial mix satisfies slump flow test and Sieve stability tests.

3.1 Test Methods [1]

Flowable Concrete is able to flow under its self-weight without segregation, bleeding without vibration and these behavior of concrete can be ensured by Flowability tests, and Sieve segregation resistance tests of concrete to determine the flow ability, passing ability and segregation resistance of Flowable according to BS: EN 12350 Part 8, 9, 10, 11, and 12[15]

Table 8
NATM Lining flowable concrete M40 Grade - Flowing ability, passing ability and segregation resistance are checked after 3 hrs. and results are as below [1].

<i>Sr.No</i>	<i>Mix</i>	<i>Slump flow (mm)</i>	<i>T500 (sec)</i>	<i>V- funnel Tf (sec)</i>	<i>V- funnel T5min (sec)</i>	<i>L-box Blocking ratio(H2/H1)</i>	<i>U-box Difference (mm)</i>	<i>Segregation Resistance</i>	<i>Remarks</i>
1	TR1	430	45.0	98	103	0.25	280	-	Not achieved
2	TR2	450	37	91	98	0.3	230	-	Not achieved
3	TR3	470	31	65	69	0.5	140	-	Not achieved
4	TR4	510	16	27	41	0.7	28	11.2	Results are found satisfactory for flowability only
5	TR5	540	5	19	22	0.76	22	7.9	Results are found more satisfactory in flowability requirements and passing ability tests

Trial mix no TR 4 has achieved all the requirements of filling ability but could not achieve the requirements of passing ability. In trial No-TR 5 achieved all the requirements of filling ability and passing ability but values are found closer to the requirements. Trial mix no TR5 has been finalized based on above-mentioned tests results values with considering TR5 can be achieved all the parameters of flowing and passing ability at site if apply some vibration during casting the structure.

Details of final NATM Lining flowable concrete M40 Grade mix design trial mix no- TR5 is as below.

Table 9: Table showing the finalized mix proportion for the flowable concrete Trial Mix No- TR 5

NATM Lining flowable concrete M40 Grade (10 MSA) [1]

Table 10
Test Results of NATM Lining flowable concrete M40 Grade in Laboratory [1]

<i>Cementitious (Kg)</i>			<i>Water (Kg)</i>	<i>Fine Aggregate M-Sand (kg)</i>	<i>Coarse aggregate (10 MSA) (Kg)</i>	<i>Superplasticizer (Kg)</i>
`Cement	GGBS	UGGBS	176	981	778	7.7
330	200	20				

<i>Test Observation</i>	<i>Property</i>	<i>Acceptance Limits as per European Guideline</i>	<i>Initial</i>	<i>1hr</i>	<i>2hrs</i>	<i>3 hrs.</i>
Slump-flow class SF1	Flowability/Filling Ability	$\geq 520\text{mm}, \leq 700\text{mm}$	630	610	580	540
T500	Viscosity Flowability	between 3–7 Sec	4	4	4.5	5
V5min	viscosity Flowability	—	18	22	24	28
V Funnel Tv VF 2	Viscosity Flowability	$\geq 7S, \leq 27s$	14	16	18	24
L Box (H2/H1)	Passing Ratio	$\geq 0,75$	0.8	0.8	0.78	0.76
U Box Deference	Height difference	30 mm Max	0	15	19	22
Sieve Segregation	Segregation Resistance	< 23 %	9.5	9.2	8.4	7.9
Ambient Temperature			26.5	27.5	28.2	29.4
Mix proportion of selected mix design TR5 implemented at site for Tunnel NATM concrete and NATM cross passages and total 11426 cum concrete quantity is executed from 25th Feb 2020to 30th june'2021.						

The flowing ability and passing ability of concrete mix are checked according to conformity criteria for the properties of Flowable concrete [4] at site and observed results are as below.

Table 11
The Average Test Results of Site executed Flowable concrete mix during concreting for Tunnel NATM Lining Concrete.

Test Observation	Property	Acceptance Limits as per European Guideline	Results obtained at Batching Plant	Results obtained (around 1 to 2 hrs after batching time)	Remarks (Comparison with 2 hrs results of TR 9)
Slump-flow class SF1	Flowability/Filling Ability	$\geq 520\text{mm}, \leq 700\text{mm}$	630	560	-20 mm than TR 5
T500	Viscosity Flowability	between 3–7 Sec	4	6	-1.5 sec than TR5
V5min	viscosity Flowability	—	-	-	Not Taken
V Funnel Tv VF 2	Viscosity Flowability	$\geq 7S, \leq 27s$	-	-	Not Taken
L Box (H2/H1)	Passing Ratio	$\geq 0,75$	-	-	Not Taken
U Box Deference	Height difference	30 mm Max	-	-	Not Taken
Sieve Segregation	Segregation Resistance	< 23 %	-	-	Not Taken
Ambient Temperature		26.5	27.5	28.2	-1.2 deg at site

All the parameters of checks are not checked at the site due to the fact shifting of all checking out equipment couldn't nearly possible at some point of concreting at the site, but slump flow, T 500 mm checks, and the temperature had been executed for 1904 transit mixers and their common values are cited in above table.

A few tests could not be conducted at the site laboratory due to the non-availability of sufficient testing apparatus at in house laboratory. Consequently, samples of specimens were sent to a third-party laboratory for undertaking assessments areas underneath.

Table 12
Hardened Concrete Test results for Tunnel NATM Lining Concrete [1].

Sl. NO.	Test Description	Acceptance Requirement as per contract specification	Actual Results obtained
1	RCPT	1000 Coulombs	782.0 coulombs
2	Permeability	10 mm	6 mm
3	Flexural strength	$> 0.7 \sqrt{f_{ck}}$ = 5.42 N/mm ²	6.25 n/mm ²
4	Split tensile strength	$> 0.5 \sqrt{f_{ck}}$ = 3.87 N/mm ²	5.01 n/mm ²
5	Drying Shrinkage	0.05 % (Max)	0.026 %
6	Moisture Moment	0.03 % (Max)	0.018 %
7	Chloride content	0.5 % (Max)	0.34 %
8	Sulphate content	3.7 % (Max)	0.35 %

Table 13
The Cube Compressive Strength for Successful Trial Mix no TR-5 for M40 NATM Lining Flowable Concrete in N/mm² [1]

The Cube Compressive Strength for Successful Trial Mix No. 1K-5 for M40 RAAM Lining Flowable Concrete in N/mm2 [1]					
Sr. No	Age of Cubes	No. Cubes Tested	Compressive Strength of Cubes in N/mm2	Avg. Compressive Strength of each Sample in N/mm2	Avg. Strength of Samples in N/mm2
1	7 days	9	39.6	40.81	40.14
2			41.2		
3			41.63		
4			38.5	39.58	
5			41.24		
6			38.99		
7			41.66	40.02	
8			38.99		
9			39.41		
10	28 days	18	58.54	59.52	61.34
11			63.49		
12			56.53		
13			63.21	60.33	
14			59.56		
15			58.22		
16			59.73	62.45	
17			63.24		
18			64.38		
19			62.98	61.63	
20			61.22		
21			60.69		
22			59.77	61.66	
23			58.55		
24			66.66		
25			60.12	62.45	
26			58.9		
27			68.33		
28	56	9	76.22	70.46	68.88
29			75.02		
30			60.14		
31			67.43	68.69	
32			66.23		
33			72.41		
34			68.93	67.49	
35			67.73		
36			65.81		

After achieving all the parameters according to the requirements of site conditions for Flowable concrete for grade M40 then same mix is implemented site for the construction of NATM tunnel lining and cross passages. The compressive strength results of site casted cubes for 7 days, 28 days and 56 days are represented in table and graph as below.

Table 14
The Compressive Strength of site casted cubes for M40 grade Flowable Concrete (in N/mm²) [1]

Sl. No	Age of casted Cubes	No. Samples	Avg. Compressive Strength of Samples in N/mm ²	% Of Compressive Strength Gaining	Standard Deviation in N/mm ²	% Of Coefficient of Variation
1	7 days	8	40.14	100.35	1.82	3.03
2	28 Days	35	60.22	150.55		
3	56 days	8	65.09	162.73		

Concrete cubes have been casted for testing of compressive strength for ongoing working structures and results are found satisfactory. Samples taken for cube compression strength of working structures, average compressive strength, standard deviation, and coefficient of variation are represented in the graph as beneath.

Table 15
RCC works Flowable Concrete M40 Grade - Flowing ability, passing ability and segregation resistance are checked after 3 hrs. and results are as below [1].

Sr.No	Mix	Slump flow (mm)	T500 (sec)	V-funnel Tf (sec)	V-funnel T5min (sec)	L-box Blocking ratio(H2/H1)	U-box Difference (mm)	Segregation Resistance	Remarks
1	TR6	380	53	-	-	-	-	-	Not achieved
2	TR7	450	45	-	-	-	-	-	Not achieved
3	TR8	450	31	91	98	0.3	230	6.8	Not achieved
4	TR9	530	7	21	26	0.6	36	7.5	Results are found more satisfactory in flowability requirements and near to passing ability tests

In trial No-TR 9 achieved all the requirements of filling ability and passing ability values are found nearer to the requirements. Trial mix no TR 9 has been finalized based on above-mentioned tests results values with considering TR9 can be achieved all the parameters of flowing and passing ability at site with apply some vibration during casting the structure to get the satisfactory surface finish.

Details of final RCC works Flowable Concrete M40 Grade mix design trial mix no- TR 9 is as below.

Table 16. Table showing the finalized mix proportion for Flowable Concrete, Trial Mix No- TR 9

RCC works Flowable Concrete M40 Grade (20 MSA) [1]

Table 17
Test Results of RCC works Flowable Concrete M40 Grade in Laboratory [1]

Cementitious (Kg)			Water (Kg)	Fine Aggregate M-Sand (kg)	Coarse aggregate (20 MSA) (Kg)	Superplasticizer (Kg)	C.W.A (Kg)
Cement	GGBS	UGGBS	161	889	988	5.98	4.6
245	200	15					

<i>Observation</i>	<i>Characteristics</i>	<i>Acceptance Limits</i>	<i>Initial</i>	<i>1hr</i>	<i>2hrs</i>	<i>3 hrs.</i>
Slump-flow class SF1	Flowability/Filling Ability	$\geq 520\text{mm}, \leq 700\text{mm}$	600	580	540	530
T500	Viscosity Flowability	between 3–7 Sec	4	4	5	7
V5min	viscosity Flowability	—	16	18	23	26
V Funnel Tv VF 2	Viscosity Flowability	$\geq 7\text{S}, \leq 27\text{s}$	13	16	18	21
L Box (H2/H1)	Passing Ratio	$\geq 0,75$	0.75	0.7	0.65	0.6
U Box Deference	Height difference	30 mm Max	23	26	31	36
Sieve Segregation	Segregation Resistance	< 23 %	9.5	9.2	8.4	7.5
Ambient Temperature				27.5	28.2	29.4
Mix proportion of selected mix design TR9 implemented at site for RCC structures i.e., Base slab, Roof slab and RCC walls and total 32508 cum concrete quantity is executed from 18th March 2020 to 30th June 2021.						

The flowing ability of concrete mix are checked according to conformity criteria for the properties of Flowable concrete [4] at site and observed results are as below.

Table 18
The Average Test Results of Site executed flowable concrete mix during concreting for RCC structures [1].

<i>Test Observation</i>	<i>Property</i>	<i>Acceptance Limits as per European Guideline</i>	<i>Results obtained at Batching Plant</i>	<i>Results obtained (around 1 to 2 hrs after batching time)</i>	<i>Remarks (Comparison with 2 hrs results of TR 9)</i>
Slump-flow class SF1	Flowability/Filling Ability	$\geq 520\text{mm}, \leq 700\text{mm}$	590	560	+ 20 mm than TR 9
T500	Viscosity Flowability	between 3–7 Sec	4	6.5	+ 1.5 sec than TR9
V5min	viscosity Flowability	—	-	-	Not Taken
V Funnel Tv VF 2	Viscosity Flowability	$\geq 7\text{S}, \leq 27\text{s}$	-	-	Not Taken
L Box (H2/H1)	Passing Ratio	$\geq 0,75$	-	-	Not Taken
U Box Deference	Height difference	30 mm Max	-	-	Not Taken
Sieve Segregation	Segregation Resistance	< 23 %	-	-	Not Taken
Ambient Temperature			27.5	28.2	29.4

All the parameters of tests are not checked at site because shifting of all testing apparatus could not practically possible during concreting at site, but Slump flow, T500 and temperature tests were carried out for 5118 Transit Mixers and their average values are mentioned in above table.

A few tests could not be conducted at the site laboratory due to the non-availability of sufficient testing apparatus at in house laboratory. Consequently, samples of specimens were sent to a third-party laboratory for undertaking assessments areas underneath.

Table 19
Hardened Concrete Test results for RCC works Flowable Concrete M40 Grade [1]

<i>Sl. NO.</i>	<i>Description of Tests</i>	<i>Acceptance Requirement of contract specifications</i>	<i>Results obtained</i>
1	Permeability	10 mm	4 mm
2	RCPT	1000 Coulombs	652.5 coulombs
3	Split tensile strength	> 0.5 $\sqrt{f_{ck}}$ = 3.87 N/mm ²	4.66 n/mm ²
4	Flexural strength	> 0.7 $\sqrt{f_{ck}}$ = 5.42 N/mm ²	6.10 n/mm ²
5	Drying Shrinkage	0.05 % (Max)	0.009 %
6	Moisture Moment	0.03 % (Max)	0.011%
7	Chloride content	0.5 % (Max)	0.22 %
8	Sulphate content	3.7 % (Max)	1.87 %

Table 20
The Cube Compressive Strength for Successful Trial Mix no TR-9 for M40 Grade flowable concrete in N/mm2 [1].

The Cube Compressive Strength for Successful Mar Mix no. Pk-9 for M40 Grade flowable concrete in N/mm2 [1].					
Sr.No	Age of Cubes	No. Specimen	Compressive Strength of Specimen in N/mm2	Compressive Strength of Sample in N/mm2	Avg. Strength of Samples in N/mm2
1	7 days	9	34.6	35.81	35.14
2			36.2		
3			36.63		
4			33.5	34.58	
5			36.24		
6			33.99		
7			36.66	35.02	
8			33.99		
9			34.41		
10	28 days	18	52.54	53.52	55.34
11			57.49		
12			50.53		
13			57.21	54.33	
14			53.56		
15			52.22		
16			53.73	56.45	
17			57.24		
18			58.38		
19			56.98	55.63	
20			55.22		
21			54.69		
22			53.77	55.66	
23			52.55		
24			60.66		
25			54.12	56.45	
26			52.9		
27			62.33		
28	56 days	9	73.22	67.46	65.88
29			72.02		
30			57.14		
31			64.43	65.69	
32			63.23		
33			69.41		
34			65.93	64.49	
35			64.73		
36			62.81		

After achieving all the parameters according to the requirements of site conditions for Flowable concrete for grade M40 then same mix is implemented site for the construction of RCC structures i.e., Base Slab, Roof slab and RCC walls. The compressive strength results of site casted cubes for 7 days,28 days and 56 days are represented in table and graph as below.

Table 21
The Compressive Strength of site casted cubes for M40 grade Flowable Concrete (in N/mm²) [1]

Sr.No	Age of Cube	No. Sample	Avg. Strength of Samples (N/mm ²)	% Of Strength Gaining	Standard Deviation (N/mm ²)	Coefficient of Variation (%)
1	7 days	9	33.87	84.68%	1.77	3.48
2	28 Days	35	50.81	127.03		
3	56 days	9	61.91	154.78		

Concrete cubes have been casted for testing of compressive strength for ongoing working structures and results are found satisfactory. Samples taken for cube compression strength of working structures, average compressive strength, standard deviation, and coefficient of variation are represented in the graph as beneath.

4 Application Of Flowable Concrete In The Structure

Following points had been ensured at the site before and during the placement of flowable concrete.

- Assessment for the placement situations of Flowable concrete either by using boom placer, long distance pipe pumping, direct placing via a chute or a concrete bucket placement.
- Shutter has been designed for the capability and withstanding in the forces of lateral stress of fresh concrete.
- Concrete pour plans were prepared for every concrete pour for maintaining sequence of concrete production from batching plant, placing at site, movements of pump and pipe's location during concreting to maintain the concrete pour rate and avoid formation of cold joints.
- Quality control tests and checks at batching plant before despatching the concrete and same tests were performed at site also before pouring at the structure.
- Avoid direct free fall of concrete more than 1.5 m height.
- Throughout concrete pouring visible observation have been completed for segregation in the formwork and determined no segregation.
- Concrete pour rate became maintained to keep away from entrainment and to restriction the strain at the formwork.
- Shutter vibrators, needle vibrators were used according to placing condition to ease of flow and reach each corner of formwork and compaction for achieving smooth surface finish after de-shuttering.

4.1 Quality Control Checks & Concrete surface finish after De-shuttering of the Structure

Appropriate technical team and testing equipment's were deployed at Batching plant, TM checking point and placement point.

Flowable concrete has been placed successfully in formwork without any break downs and obstacles due to proper planning and systematic arrangement. After De-shuttering NATM tunnel lining, Cross passage lining RCC walls concrete surfaces found smooth.

5 Conclusion

1. Flowable concrete can be easily placed in long distance pumping and in obstacles due to dense reinforcement of structure with some vibration during the placement.
2. Flowable concrete can be developed using low fine content with proper optimization i.e., TR9 and can be implemented at site with some vibration.
3. Optimization of powder content and fine content with higher side helps good results of flowability and possibility without vibration i.e., concrete mix TR 5 as compared to TR 9.
4. Crystalline waterproofing admixture plays effective role for reducing permeability and increase durability of the structures.
5. Water permeability tests and RCPT values found less in low cementitious concrete i.e., TR 9 due to adding of crystalline waterproofing admixture as compared to high cementitious concrete trial mix no TR 5.
6. More impermeable and durable concrete can be developed in optimized cementitious content using crystalline waterproofing admixture in the concrete mix.

Declarations

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Compliance with ethical standards

Conflict of interest - On behalf of all authors, the corresponding author states that there is no conflict of interest.

References

Figures

Figure 1

Slump Flow Test

Figure 2

Funnel test

Figure 3

L-Box test

Figure 4

U- Box Test

Figure 5

Sieve Segregation resistance Test

Figure 6

Graphical representation for Compressive Strength of site casted cubes for 7 days, 28 days and 56 days

Figure 7

Graphical Representation of site casted Cube Compressive Strength for Tunnel NATM lining flowable concrete M40 Grade.

Figure 8

Graphical representation for Compressive Strength of site casted cubes for 7 days, 28 days and 56 days

Figure 9

Graphical Representation of site casted Cube Compressive Strength for flowable concrete M40 Grade

Figure 10

Actual site photographs during concrete placing at site showing two stages of concrete pouring and no's of bends to reach at placement point.

Figure 11

Smooth surfaces of the cast in situ flowable concrete

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