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Design Approach to Incorporate Unique Performance Characteristics of Special Concrete

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***Abstract*—**The advancement in various concrete ingredients like plasticizers, additives and fibers, etc. has enabled concrete technologists to develop many viable varieties of special concretes in recent decades. Such various varieties of concrete have significant enhancement in green as well as hardened properties of concrete. A prudent selection of appropriate type of concrete can resolve many design and application issues in construction projects. This paper focuses on usage of self-compacting concrete, high early strength concrete, structural lightweight concrete, fiber reinforced concrete, high performance concrete and ultra-high strength concrete in the structures. The modified properties of strength at various ages, flowability, porosity, equilibrium density, flexural strength, elasticity, permeability etc. need to be carefully studied and incorporated into the design of the structures. The paper demonstrates various mixture combinations and the concrete properties that can be leveraged. The selection of such products based on the end use of structures has been proposed in order to efficiently utilize the modified characteristics of these concrete varieties. The study involves mapping the characteristics with benefits and savings for the structure from design perspective. Self-compacting concrete in the structure is characterized by high shuttering loads, better finish, and feasibility of closer reinforcement spacing. The structural design procedures can be modified to specify higher formwork strength, height of vertical members, cover reduction and increased ductility. The transverse reinforcement can be spaced at closer intervals compared to regular structural concrete. It allows structural lightweight concrete structures to be designed for reduced dead load, increased insulation properties. Member dimensions and steel requirement can be reduced proportionate to about 25 to 35 percent reduction in the dead load due to self-weight of concrete. Steel fiber reinforced concrete can be used to design grade slabs without primary reinforcement because of 70 to 100 percent higher tensile strength. The design procedures incorporate reduction in thickness and joint spacing. High performance concrete employs increase in the life of the structures by improvement in paste characteristics and durability by incorporating supplementary cementitious materials. Often, these are also designed for slower heat generation in the initial phase of hydration. The structural designer can incorporate the slow development of strength in the design and specify 56 or 90 days strength requirement. For designing high rise building structures, creep and elasticity properties of such concrete also need to be considered. Lastly, certain structures require a performance under loading conditions much earlier than final maturity of concrete. High early strength concrete has been designed to cater to a variety of usages at various ages as early as 8 to 12 hours. Therefore, an understanding of concrete performance specifications for special concrete is a definite door towards a superior structural design approach.

***Keywords*—**High performance concrete, special concrete, structural design, structural lightweight concrete.

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I. Introduction

VARIOUS special varieties of concrete are available commercially for usage at construction sites. Such varieties of concrete are produced and proportioned on the basis of improvement of one or more performance characteristics of concrete in green or hardened state. Apart from achieving the routine characteristics like workability and 28-days compressive strengths, the characteristics modified in order to manufacture above special concrete varieties are compressive strength at various other ages, flowability, porosity, equilibrium density, flexural strength, elasticity, permeability, etc. The modified properties and mixture proportions used to arrive at those results are demonstrated in this paper. This is achieved by using specialized additives, plasticizers, and fibers.

The enhanced properties of these concrete varieties have been evaluated in terms of changes in structural and construction design approach. By leveraging the improved performance parameters, traditional design can be modified to improve the end use characteristics of the structures and significantly reduce the cost of construction at various stages, thus, impacting the overall life cycle cost of the structure. This paper approaches this subject through some case studies for some structures where these concrete varieties have been used in construction scenario in India.

I. Self-Compacting Concrete (SCC)

A. Technical Characteristics Specified

According to European guidelines [1], SCC is broadly classified in SF1, SF2 and SF3 (Fig. 1) based on application area and their subsequent performance requirements. The use of SCC is demonstrated by its use in Mumbai Monorail project, where the concrete flow was classified under SF3 category. The project needed to cast 500 nos. 10-meterhigh piers and 600mm wide beam girder stitches. The compressive strength required for these elements was M45 for piers and M60 for beam girder joints. Apart from durability parameters and early strength requirements, the structural elements were also expected to demonstrate good aesthetic appearance by way of superior surface finish. In order to achieve this extraordinary performance coupled with time bound completion schedule of the project, SCC was selected as preferred concrete type.

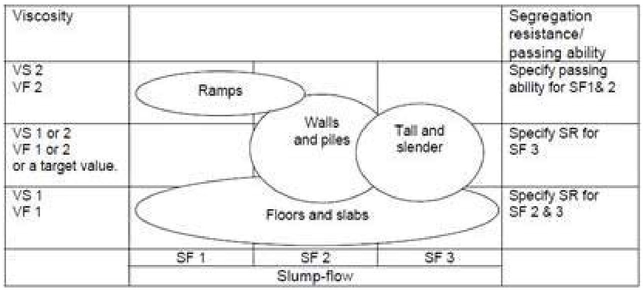

Fig. 1 Properties of SCC for various types of application [1]

A smaller maximum size of aggregates of 12.5 mm was used considering vertical application in a very congested structure. Various mixture parameters and measured values are recorded in Table I.

TABLE I
SUMMARY OF TARGET SCC CLASSES FOR MONORAIL PIERS AND GIRDER JOINTS

Measured Value	Class	Test Method	Characteristics
760-850 mm	SF3	Slump Flow	Flowability/Filling ability
2.5 Secs 10 Secs	VS1/VF1	T500 V Funnel	Viscosity/Flowability
85%	PA1	L- Box	Passing ability
<20%	SR2	sieve segregation	Segregation resistance

B. Typical Mixture Proportions

Concrete mix proportions approved after extensive laboratory and field trials using varied combinations of admixtures successfully for SCC mixes are demonstrated in Table II for reference. Long term strength gain of these mixes was also tested for upto one year. A consistent quality of SCC with an excellent standard deviation of 3.9 was produced.

TABLE II
MONORAIL SCC MIX PROPORTIONS AND RESULTS

365 Days	28 Days	7 Days	w/b ratio	Total Binder	Grade
70.87	52.16	34.21	0.33	535	M-45SCC
87.02	63.24	44.34	0.29	620	M-60SCC

C. Impact on Design Procedures

Hydrostatic pressure on formwork due to high fluidity increases with use of SCC. Often, full hydrostatic pressure is assumed, requiring strengthening of formwork and subsequent costs, unlike normal concrete where a reduction in head occurs. However, this is not always the case. Tests performed by Vanhove and Djelal [2] show that when determined using overall height of the structure, the maximum hydrostatic pressure at 1.5-meter height on the wall is 64% to 68% depending on the placing rate.

This would require change in formwork design to accommodate the additional loading. However, the live load on formwork is reduced due to reduction in finishing manpower and vibrators. Formwork design for SCC mixtures must account for the liquid head of the highly fluid concrete. ACI 237 [3] informs contractors that formwork designs accounting for full liquid head can allow them to take advantage of the rapid casting rates possible with SCC. While formwork designed for full liquid head cost more than conventional formwork, on projects such as this, costs are offset through scheduling improvements, cutting the number of placements in half, and reduced labor. From the design and placement standpoint, specialized forms would eliminate horizontal joints, allow the use of continuous vertical reinforcement, and minimize concerns associated with consolidation and cold joint issues that must be taken into account with slower placements.

Height of casting of columns and vertical structures can be increased without sacrificing the surface finish and degree of compaction. Traditional construction methods allow for a maximum 3-meter lift with a maximum free fall of 1.2 meters, thereby limiting the monolithic casting of long columns and walls. In this particular case, the height of the columns was 10 meters (Fig. 2). For example, Taiwan Expressway No. 6 project used SCC for columns as tall as 65 meters [5].

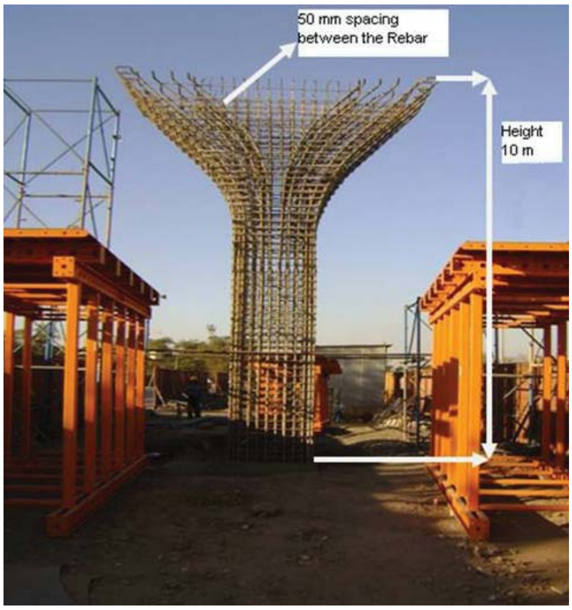

Fig. 2 Typical column detailing of Mumbai Monorail piers

Transverse reinforcement detailing plays a crucial role in deciding spacing due to constructability considerations, thereby limiting its effectiveness against shear and cracking. With SCC, reinforcement spacing can be reduced [4].

Span of concrete flow within the member can be 10-15 meters when SCC is used to cast the structure in line with European guidelines clause 8.5.2 [1].

D. Improvements and Savings

Investigation was carried for a structural slab to seek opportunities for design and construction savings by using SCC as the build method for individual structural element. The intention of this study was to assess the benefits of SCC in terms of speed of construction, labour and machinery. Based on data obtained from construction sites, SCC can typically be placed using one third of the labour and a quarter of the time of conventional concrete in most situations, which delivers savings in overall project duration. Table III below uses the cost modeling for a typical slab, depicting 50% and 66% reduction in equipment and labour cost, respectively.

TABLE III
BREAKDOWN OF COST SAVINGS FROM USING SCC IN TYPICAL SLABS

	SCC	PC	
Rs/day	300	300	Supervisor
Rs/day	0	460	Labour for Placement
Rs/day	0	920	Labour for Vibrator
Rs/day	460	460	Labour for finishing
Rs/day	760	2140	TOTAL
M3/ Hr	20	10	Rate of pour
hours	9.58	19.16	Hours required
days	2	3	Days required
	₹ 1,520.00	₹ 6,420.00	LABOR COST
Rs	33531.55	33531.55	PUMP
	0	6000	Vibrator
	₹ 33,531.55	₹ 39,531.55	EQUIPMENT COST
Rs/Cum	4600	4200	Concrete
Rs	₹ 881,401	₹ 804,757	
	₹ 914,932	₹ 844,289	TOTAL
Rs/Sft	0	5	Repairing cost for defects
Rs	₹ 0	₹ 100,000	Total Repairing Cost
	₹ 916,452	**₹ 950,709**	POUR COST :

Additionally, other design benefits can be leveraged from SCC since, for the above study, the slabs were designed using the same mechanical properties as conventional base case concrete. However, there are cost reductions possible for structures derived from superior finish, improved surface characteristics, minimized rework, low noise levels, flexibility for night concreting, etc.

II. STRUCTURAL LIGHTWEIGHT CONCRETE (SLWC)

A. Technical Characteristics Specified

ACI 213 [6] defines structural lightweight concrete as the concrete with equilibrium density less than 1850 kg/m^3 [5]. In India, various lightweight aggregates available are based on calcined clay, sintered fly ash, and pumice stone. Various researches using local materials have been done to ascertain that major performance characteristics of concrete using these aggregates conform to the requirements laid down by the concrete specifications. As seen in Fig. 3, the unit weights of fresh mixtures tested vary between 2100 kg/m^3 and 1750 kg/m^3, with 4% less dry unit weight, i.e. 2050 to 1700 kg/m^3. Mixes with 30% replacement of cement with fly ash were also tested. The density of SLWC is 25% lower than the density of normal weight concrete.

B. Typical Mixture Proportions

The structural lightweight concrete for commercial use has been proportioned with binder content of 500 kg/m^3 and water binder ratio of 0.35. In order to compensate the reduction in strength due to lightweight aggregates, fly ash and densified silica fume were also added to the concrete. The mix proportions for the successful SLWC concrete mixes are presented in Table IV.

The concrete produced with lightweight aggregate exhibited 28-day compressive strength of 48.25 MPa and 40.08 MPa. The compressive strength results at various ages are presented in Table V. The tensile and flexural tests were also carried out. The 28-day flexural and tensile strengths were found to be 15 MPa and 8 MPa, respectively. From the above results, it can be seen that lightweight concrete with compressive strength class of M30 can be easily obtained using various lightweight aggregates at density of 2000 kg/m^3 and below.

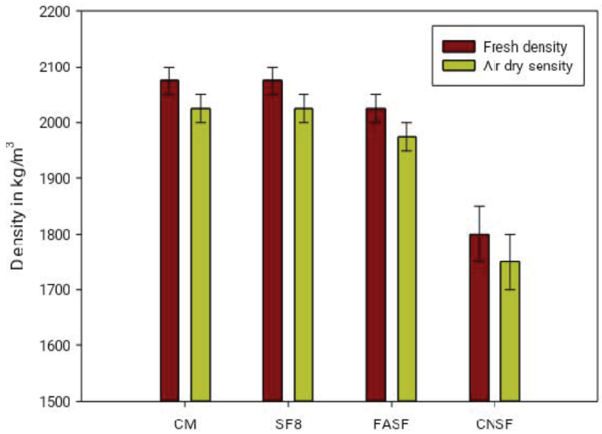

Fig. 3 Densities of some SLWC mixes

TABLE IV
CONCRETE MIX PROPORTIONS FOR SLWC

FASF	SF	Mix ID
310	460	Cement (kg/m^3)
150	0	Flyash (kg/m^3)
40	40	Silica fume (kg/m^3)
0	0	Cenosphere (kg/m^3)
339	351	20 mm aggregate (kg/m^3)
306	315	10 mm aggregate (kg/m^3)
657	678	Fine aggregate (kg/m^3)
175	175	Water (kg/m^3)
1977	2019	Theoretical density (kg/m^3)

TABLE V
COMPRESSIVE STRENGTH RESULTS OF SLWC

28 day	7 day	3 day	Mix ID
48.25	40.44	28.01	SF8
40.08	27.86	14.2	FASF

C. Impact on Design Procedures

From the study, it is clear that workable and non-segregating structural lightweight concrete can be commercially produced to have fresh densities lower than 2000 kg/m^3 with compressive strengths beyond 40 MPa. The unit weight of concrete as low as 1750 kg/m3 with compressive strength of 34 MPa. In addition, the obtained tensile and flexural strengths of lightweight concrete are on par with the normal concrete. Hence, such reductions in unit weight can have important benefits on the performance of structures. One such example is Raftsundet Bridge, a 711-meter box girder bridge in Northern Norway [7]. The main span has 298 meters length and is constructed using high performance lightweight concrete with 28 days compressive strength of 60 MPa.

Dead load reduction in a concrete structure decreases the stresses in the structural elements, and forces acting on the foundations of the structure are also reduced. Thus, with a lower total weight of the structure, the structural details of the elements can be optimized; lower amounts of reinforcing steel and reduced cross sections can be obtained, which is important from an economical point of view, too.

Reduced formwork pressure due to lower unit weight of the concrete is also beneficial in terms of formwork cost.

D. Improvements and Savings

Lower overall cost of the structure can be obtained as a result of the reduced weights. The stresses generated due to seismic loads are also dependent on the weight of the structure, reduction of the structural weight is beneficial in terms of earthquake resistance.

Apart from the above, the impact of SLWC has potential for further investigation in terms of reduction in building mass, increase in thermal efficiency, improvement in fire retardant properties, and resistance to seismic forces. SLWC precast elements have been proven to have reduced transportation and placement costs [7].

III. Steel-Fiber Reinforced Concrete (SFRC)

A. Technical Characteristics Specified

Internal roads for a factory in Pune, India was proposed to be constructed using traditional RCC. Steel reinforcement were proposed on both sides with 8mm tor steel with spacing 250mm. Depth of RCC was designed to be 150mm, with 100mm thick PCC, 150mm water bound macadam subbase over a 230-mm soil base and 600mm hard murrum soil subgrade.

Steel-fiber reinforced concrete was proposed as an alternative solution to the requirement. Fibres arrest shrinkage cracks of the concrete, increase fire resistance, impact and blast resistance. Additional flexural strength makes it ideal for abrasive surfaces like roads, pavements and industrial floors. SFRC imparts improvement in impact and fatigue resistance to concrete as shown in Fig. 4.

Plain concrete possesses a very low tensile strength, limited ductility and little resistance to cracking.

B. Typical Mixture Proportions

Mix proportioning of SFRC is by and large similar to normal concrete. Selection of materials is influenced by local availability and prices. Compressive strength classes determine binder content and water-binder ratios. Choice of admixtures is governed by atmospheric conditions and compatibility with cement. Admixtures are commonly used with SFRC to improve workability and finishability of the concrete. If more than one type of admixture is used, each should be batched separately in order to maintain the accuracy and minimise errors. For high dosage rates the mix design should be optimized in view of workability and pumpability. The water/cement ratio should not exceed 0.55. The dosage of steel fibers is selected as per design procedures discussed in next section.

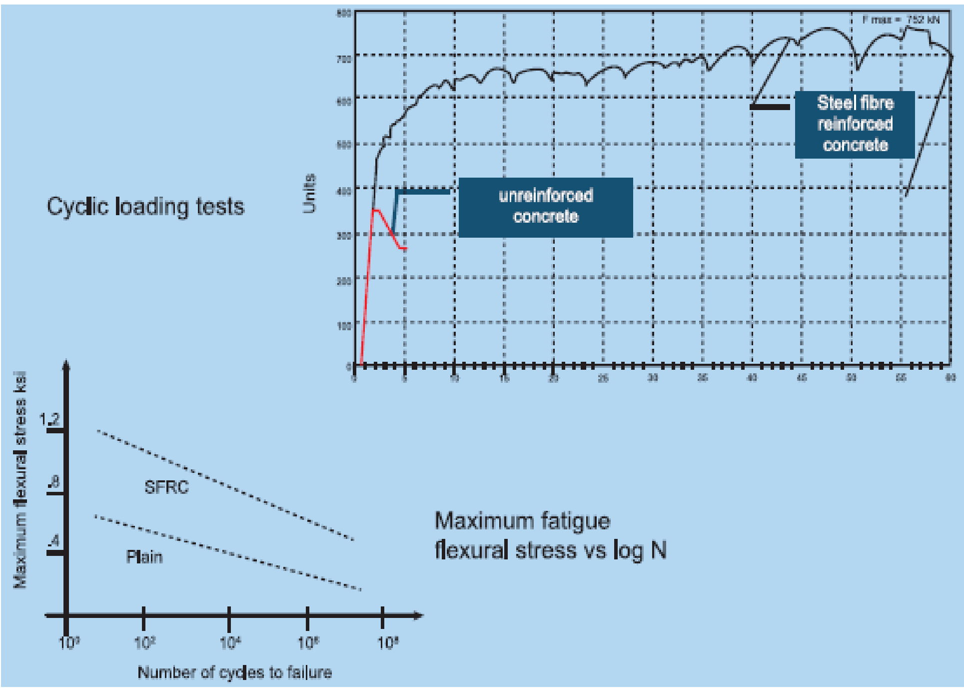

Fig. 4 Impact and fatigue resistance of SFRC

Following concrete characteristics have been applied in this project mixture proportions:

Compressive strength: M25/30
Flexural strength Ffctk: 3.40 N/mm²
Ffctm: 4.30 N/mm²
E-modulus Ec: 30500.00 N/mm²
Poisson Coefficient Vc: 0.15
Relaxation factor Kc: 2.6
Shrinkage factor (‰): 0.4

C. Impact on Design Procedures

Replacement of primary steel reinforcement can be accomplished to achieve pavement performance while taking benefits available in while using SFRC. Following design criteria were adopted for the pavement:

K value: 0.050 N/mm³

For ultimate limit state, the governing load case is one pointload - Saw Cut 27.47 kNm/m. For serviceability limit state, the governing load case is one pointload - Saw Cut 29.35 kNm/m.

Coefficient of friction (μ) between slab and subbase: 0.50

To consider the load transfer, a large concrete slab is traditionally divided into smaller areas by means of contraction joints. Aggregate interlock enables to transfer part of the load to the adjacent slab(s). The values taken in this design are based the PCA document for unreinforced concrete. The designed SFRC floor parameters are as follows:

Floor thickness: 200 mm
Dosage: 20.00 kg/m³
Fiber type: 3D 80/60BG
Re,3 value: 53.49%
Equivalent flexural strength (Ffct, eq,150): 2.30 N/mm²
Max joint spacing: 4000.00 mm * 4000.00 mm

D. Improvements and Savings

The cost savings per panel based on two SFRC options proposed are given in Table VI.

TABLE VI
COST COMPARISON OF SFRC SLAB ON GROUND VS. RCC PAVEMENT SLAB

SFRC Option2	SFRC Option1	Plain Concrete	Units	Parameters
200	150	150	mm	Slab Thickness
600	450	450	Rs./m^2	Concrete
		156	Rs./m^2	Steel Rebar
		58.5	Rs./m^2	Steel Chairs
327.6	283.5		Rs./m^2	Steel Fiber
0	110	220	Rs./m^2	PCC
927.6	843.5	884.5	Rs./m^2	Total Savings

In addition, usage of SFRC offers many indirect cost and constructability advantages like speed of execution, flexibility of equipment usage for achieving flat and level floors, etc. There is a great potential for using SFRC in other flexural members, thereby allowing for steel reduction and superior composite properties. Hassanzadeh and Sundquist conclude that the observed ultimate loads indicate that the utilisation of steel fibresinconcrete has a significant influence on increasing the ultimate load capacity of the slabs and increase of the punching shear capacity of slabs due to adding steel fibre to the high strength concrete is about 36% [8].

IV. High Early Strength Concrete (HESC)

A. Technical Characteristics Specified

HESC can be designed for various strength classes with target strengths at various early ages. This study utilizes various applications of a proprietary high early strength concrete commercially called Rapid Concrete which is also a high 28-day strength concrete, with mixes typically tailored to achieve the typical range of 18-30 MPa at 24 to 48h. Fig. 5 displays the comparison of strength gain pattern at early age in logarithmic scale.

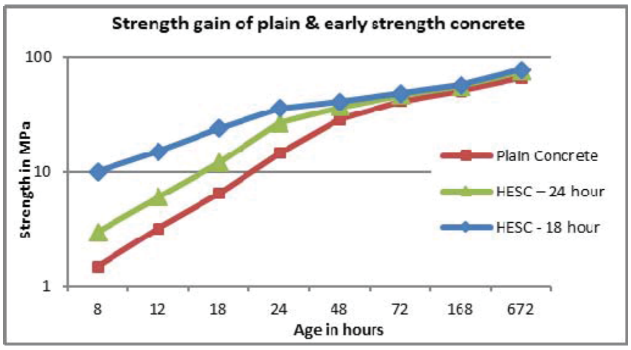

Fig. 5 Comparison of early strength gain pattern of plain and high early strength concrete

B. Typical Mixture Proportions

Mix proportioning of HESC focuses primarily on selection of suitable and compatible combination of cement, supplementary binders, superplasticizers and accelerating additives. Factors such as paste content, water content and fine aggregate to coarse aggregate proportioning also have some influence on its properties.An understanding of hydration process and temperature regime is helpful in making proper mix proportion selection.

C. Impact on Design Procedures

HESC also enables early formwork removal and accelerate construction site schedules. Removal of form work depends upon achievement of reasonable strength gain in the early age of concreting (7 days for slab and 3 days for columns and vertical elements). Once formwork (shuttering) is removed from structure it can be reused for concreting of other structural elements, early strength gain can help in reducing the rotation time of formwork. This can help in optimizing the use of formwork which forms major part of any construction project.

HESC can double the number of daily rotations of formwork for walls, columns, slabs on grade and grade beams, allowing greater flexibility in construction schedules in relation to the rotation of formwork. This provides an opportunity to regain project time lost due to climatic conditions, breakdown, etc.

Construction activities are mostly dependent on progress of preceding activities. In most cases construction of new structural element cannot begin, unless the previous structural element has achieved 65% of its design strength. For example, a new slab cannot be cast unless the column beneath achieves 65% of designed strength, by using HESC, project team can accelerate the strength gain and thus enable faster loading of the structural element.

D. Improvements and Savings

Design benefits which make use of HESC's high ultimate 28 days strength should be considered with respect to the possibility of either reducing the member dimensions or reducing reinforcement volume. The comparison of these cost evaluations was made with a base case to evaluate cost savings and increase in floor space. To facilitate holistic comparisons, costs calculation for these four scenarios are presented as an approach towards specific design calculation :

- Base Case : Conventional M35 Grade of Concrete
- Project Duration Only Saving: Use of HESC as a straight substitution for Standard Mix
- Project Duration and Design Saving (Reduced reinforcement and no change to element size) using HESC Mix
- Project Duration and Design savings (Reduced member size and no change to reinforcement) using HESC Mix

The approach was to redesign the elements by providing equivalent structural performance to the elements as designed in the building. The actual construction sequence used by the contractor on the project was studied and reductions in project duration attributable to the use of HESC were evaluated. Changes in design would reduce the material required (i.e. smaller sections and less reinforcement) and lower the time required for pour. A similar study was carried out by Tarmac in association with ARUP to evaluate use of Special Concrete at design stage [9].

HESC's high early strength gain has the potential to realize additional project duration savings. Table VII shows how the costs (in Rs./m3) vary when using HESC compared to the base case, taking into consideration duration only savings, reduced reinforcement and duration savings and reduced size and duration savings.

TABLE VII
DESIGN COST (RS/CUM) SAVINGS IN HESC USAGE

Duration/ Size	Duration/ Rebar	Duration Only	Base	
7371	8000	8000	6500	Concrete
4950	4405	4950	4950	Rebar
4000	4000	4000	8000	Formwork
197	200	200	200	Plant
6000	6000	6000	6000	Labour
22518	22605	23150	25650	Total
-12.2%	-11.9%	-9.7%		Saving

This study has found potential design benefits and cost savings from using HESC at an elemental level. Columns show significant cost savings due to reduced size and/or reinforcement quantity. Reducing column sizes brings additional benefits such as improved aesthetics and increased carpet area.

Additionally, this concrete variety has been proven to be very beneficial in the instances of road repairs and other building repair works, to enable early commissioning of the repaired structure.

V. SUMMARY OF DESIGN PRINCIPLES

There are further many varieties of special concrete apart from the above varieties, which offer specifically designed performance characteristics that impart functional benefits to the construction process and the structure lifecycle. Such engineered concrete can be utilized with much advantages and cost savings in construction projects. This task can be accomplished by incorporating the modified characteristics like early strength, flexural strength, shrinkage, viscosity, density, permeability, conductivity etc. in the structural and construction design process.

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