Steel Reinforced Reactive Powder Concrete

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***Abstract*— *RPC is an emerging technology that lends a new dimension to the term "high performance concrete". It has immense potential in construction due to superior mechanical and durability properties than conventional high performance concrete, and could even replace steel in some applications. The development of RPC is based on the application of some basic principles to achieve enhanced homogeneity, very good workability, high compaction, improved microstructure and high ductility. RPC has an ultra-dense microstructure, giving advantage of waterproofing and durability characteristics. It could, therefore be a suitable choice for industrial and nuclear waste storage facilities. This paper presents the experimental procedure for the design of self-compacting Reactive Powder Concrete, in which we proposed the mix proportion with the globally acceptance result of all tests and the carried out test are slump flow test and V-funnel test. The mix consists of 85%of cement,15% of silica fume(as a cement replacement material), Fine aggregate(river sand), Quartz powder ,4% superplastizer and varying percentage of steel fibres. The compressive strength, split tensile strength and flexural strength was checked on the 3-day, 7-day and 28-day and results are indicating that the proposed mix can produce self-compacting reactive powder concrete (Ultra High Performance Concrete)with higher quality. Ultra High-performance concretes are made with carefully selected high-quality ingredients and optimized mixture designs; these are batched, mixed, placed, compacted and cured to the highest industry standards. Typically, such concretes will have a low water-cementing materials ratio of 0.20 to 0.45. Super Plasticizers are usually used to make these concretes fluid and workable. Ultra High-performance*(i) *concrete almost always has a higher strength than high*(ii) *performance concrete.*

Keywords*— *Quartz powder*, *Reactive Powder Concrete, silica fume, steel fibers and super plasticizer.

I. INTRODUCTION

Reactive powder concrete (RPC) is ultra-high strength and high ductile composite material with advanced mechanical properties. Reactive powder concrete is a concrete without coarse aggregate, but contains cement, silica fume, sand, quartz powder, super plasticizer and steel fibre with very low water binder ratio. The absence of coarse aggregate was considered by inventors to be key aspect for the microstructure and performance of RPC in order to reduce the heterogeneity between cement matrix and aggregate.Reactive Powder Concrete, also known as Ultra-High Performance Concrete, can be even stronger, with strengths of up to 800 MPa (116,000 PSI) which can be easily by eliminating large aggregate completely, carefully controlling the size of the fine aggregates to ensure the best possible packing, and incorporating steel fibers into the matrix.RPC is an ultra-high-strength and high ductility cementitious composite with advanced mechanical and physical properties. It is a special concrete where the microstructure is optimized by precise gradation of all particles in the mix to yield maximum density. It extensively uses the pozzolanic properties of highly refined silica fume and optimization of the Portland cement chemistry to produce the highest strength hydrates.

This new material demonstrates greatly improved strength and durability characteristics compared with traditional or even high-performance concrete. The improved properties of RPC are obtained by improving the homogeneity of the concrete by eliminating large aggregates, increasing compactness of the mixtures by optimizing packing density of fine particles, and using fine steel fibers to provide ductility.

II. TYPES OF REACTIVE POWDER CONCRETE

The RPC family includes two types of concrete, which offer interesting implicational possibilities in different areas they are,

RPC 200

RPC 800

RPC 200 uses a combination of fine quartz, silica, silica fume and cement to form a cementitious matrix supporting straight and smooth steel fiber reinforcements. These steel fibres are generally 13 mm long and have a diameter of 0.15 mm. The addition of super and hyper-plasticizers allow for the cement to be mixed with approximately the same ease as conventional concrete. Obtaining a compressive strength of 170MPa when curing for 28 days at ambient temperature and 230MPa when curing at 90 degrees Celsius for 6-12 hours after pre-curing at ambient temperature for 2 days. They found that the fracture energies varied from 15,000 J/m2 to 40,000 J/m2 depending on the amount of steel fibre added to the mix. The maximum stress encountered was approximately ten times greater than the displacement at the opening of the first crack.

RPC 800 is restricted in its use to small or medium sized pre-fabricated structural elements such as bridge bearings, security vaults and waste/transportation vessels. The composition of RPC 800 proposes by Richard and Cheyrezy is similar to RPC 200 although steel fibres are replaced by a stainless steel microfiber, less than 3mm long. RPC 800 is cured at 250 degrees Celsius after de-moulding and a compressive force is generally applied while in the mould. Richard and Cheyrezy experimented with the use of steel powder instead of quartz sand and reached compressive strengths of up to 800MPa and fracture energies of 1,500 J/m2.

III. LITERATURE REVIEW

The following literature review discusses the mix proportion, properties, design, and applications of RPC. In addition, a brief summary of the modeling of RPC in compression as well as tension were presented. Also, some reports from American Concrete Institute (ACI) for fibre reinforced concrete were presented.

- **RPC – MIX PROPORTIONS**

Dattatreya. J.K., et al., (**2007)**studied several particle packing models to develop a mix proportion for the reactive powder concrete. The optimization of granular packing of the ingredients was an important factor for getting enhanced mechanical and durability properties. The granular packing of materials like silica fume, quartz powder, standard sand with cement were optimized and the experimental results were compared with the theoretical packing models.**Plawsky.J. et al., (2002)** explored a new method for dispersing cement in sand to produce dry premix with better mechanical and physical properties. The problems in blending the dry materials and the dispersion of water were identified. In addition, the understanding of mixing process leads to design the future generation equipments to produce dense-mortar.

- **RPC** – NON-DESTRUCTIVE TESTS

(RPCGlenn Waher, et al.,(2004) conducted non-destructive tests on reactive powder concrete) using traditional piezoelectric transducers with center frequencies of 500 kHz and 1MHz. Also longitudinal and shear wave velocities were found. These data combined with mass density were used to determine the modulus of Elasticity of RPC material. The results were compared with the static moduli measurements conducted according to ASTM469. This comparison gives a correlation coefficient of 0.94 indicating a high correlation by these two different of the dynamic and static moduli of elasticity.

- **RPC – DURABILITY PROPERTIES**

Harish.K.V., et al.,(2008) investigated an ultra high performance concrete at CSIR-SERC., Chennai. It was found that the selection of ingredients and curing regime plays a major role in the enhanced performance of UHPC. It was found that addition of silica fume increases the strength of concrete due its high pozzolanic activity. In addition, the types of curing regime was (normal water, hot water, hot air) recommended to achieve high mechanical properties. A mix proportion has been developed by optimizing the volume of ingredients and curing regime to produce ultra high strength concrete of 193MPa.

- **RPC – MECHANICAL PROPERTIES**

Kim.D.J. et al.,(2008) investigated the flexural behaviour of fibre reinforced cement concrete with four different types of fibres(high strength steel twisted-T, high strength steel hooked=H, high molecular weight polyethylene spectra-SP, and PVA fibres) and two volume fraction contents 4% and 1.2%. The tests were carried out according to ASTM standards. The T-fibre specimens showed superior mechanical properties while the PVA fibre concrete was the inferior one. whereas the SP-fibre exhibited the highest deflection at maximum load The test results from both experimental programs were used to critique the new ASTM standard [C 1609/C 1609M-05], and a few suggestions were made for improving the applicability of the standard to deflection for hardening FRCCs.

Cwirzen.A., et al., (2008) developed a new Ultra high strength mortar(UHS) concrete (both treated and non-treated) and tested for frost durability properties. The 28 day compressive strength varied from 170-202MPa for heat treated concrete and for non-heat treated Concrete the strength varied from 130-150MPa. Other tests were carried out for creep and shrinkage, which showed improved values when compared with ordinary concrete. A number of tests were carried out to establish the correlation between the water demand wetting time, mix composition, rheological and the mechanical properties. Quarz micro-fillers were used to improve the packing density. The study of hybrid concrete beams indicated the formation of low strength transition zone between the UHD and Normal strength concretes.

- **RPC-DESIGN CONSIDERATIONS**

Lai.J and Sun.W.(2010)conducted experiments to find the spalling strength of Reactive Powder Concrete(RPC) using Hopkinson bars. RPC specimens with different dosages of steel fibres were subjected to impact of the projectile at the free end. The compressive waves and reflected tensile waves were recorded. Also a finite element analysis were carried out by simulating using the material model JHC (JOHNSON HOLMQUIST CONCRETE) (LSTC 2003) and found suitable.

- **RPC – APPLICATIONS**

Chin – Tsung et al.,(2007) proposed a Reactive powder mortar(RPM) of flow value 200% and compressive strength of 75MPa for repair and rehabilitation. Series of tests like slant shear, rebar pull out, tensile tests were performed and the results were compared with the cylinders repaired with epoxy resins. The strength of cylinders with RPM mortar was higher while the slant shear strength is almost equal to that of epoxy resin.

- **BOOKS AND REPORT**

Ivan Markovic (2006)inthe research project presented for *his Ph.D. thesis* developed an innovative type of fibre concrete, with improved tensile and ductile properties. The concrete mixture was combined with short and long fibres (13mm and 30mm long fibres). The short fibres are straight and long fibres were hooked. All-important aspects like compressive tests, pullout tests for single fibres, flexural tests, and uniaxial tensile tests were carried out for various combinations of fibres. A new analytical model for bridging cracks by fibres were developed and successfully implemented for tensile softening response of HPC. Also, the utilization of HPC in the Engineering Practice was discussed, including a case study on light prestressed long-span beams made of HPC.

IV. ADVANTAGES OF RPC

- As fracture toughness is higher, RPC exhibits high ductility.
- Since RPC is an Ultra dense micro structure, porosity and permeability is less and therefore can be used for waste storage holding facility.
- RPC has limited shrinkage, increased corrosion resistance and so can be used inaggressive chemical environments.
- Its superior strength combined with higher shear capacity results in significant dead load reduction and limitless structural member shape.
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- With its ductile tension failure mechanism, RPC can be used to resist all stresses except direct primary tensile stresses. This eliminates the need for supplemental shear and other auxiliary reinforcing steel.
- RPC improve seismic performance reduces inertia loads with lighter members. Reduced cross sections of members provides higher energy absorption.
- Low and non-interconnected porosity reduces mass transfer, making penetration of liquid/gas or radioactive elements nearly non-existent.

V. LIMITATIONS OF RPC

- The least costly components of conventional concrete are basically eliminated or replaced by more expensive elements.
- The fine sand used in RPC becomes equivalent to the coarse aggregate of conventional concrete
- The Portland cement plays the role of the fine aggregate and the silica fume that of the cement of conventional concrete.
- The mineral component optimization alone results in a substantial increase in cost over and above that of conventional concrete (5 to 10 times higher than HPC)
- Applying pressure to mix and applying heat treatment in the field has got technological difficulties and cost.
- RPC should be used in areas where weight savings can be realized
- Since RPC is in its infancy, the long-term properties are not yet known.

VI. MATERIALS AND METHODS

RPC is composed of similar modulus of elasticity and size increasing homogeneity reducing differential tensile strain. The material having the largest particle size in RPC is sand. It composed of very fine powders (cement, sand, quartz powder, steel aggregates and silica fume), steel fibers (optimal) and a superplasticizer. The superplasticizers, used at its optimal dosage, decrease the water to cement ratio (w/c) while improving the workability of the concrete. A very dense matrix is achieved by optimizing the granular packing of the dry fine powders. This compactness gives RPC, ultra-high strength and durability

- *Cement*

Cement is binding material for production of primary hydrates. Its particle size ranges from 1µm to 100µm. Optimum cement properties are C_3S: 60% C_2S: 22% C_3A: 3.8% C_4AF: 7.4%

- *Fine aggregates (river sand or natural sand)*

Coarse aggregates are replaced by fine sand. It gives strength to the concrete. Maximum size of sand is 600µm. Size ranges from 150µm to 600µm. It eliminates mechanical chemical and thermo mechanical failures.

- *Quartz powder*

Its particle size ranges from 5µm to 25µm. It mustbe in crystalline form.

- *Silica fume*

Silica fume is used for filling voids and enhance rheology and for production of secondary hydrates. Its particle size ranges from 0.1µm to 1µm . Steel fibers
It should have good aspect ratio and should be able to improve ductility. Its length ranges from 13mm to 25mm. It should be straight.

- *Super plasticizer (Sulfonated napthaleneformaldehyde)*

A copolymer of acrylic ester (CAE), a polynaphtalene Sulfonate (PNS) and a employed for the purpose. These admixtures are synthetic polymers polymelamine sulfonate (PMS) are normally.

VII. PRILIMINARY INVESTIGATION

Table .1: Components of RPC and Their Properties

Sl. no	Sample	Specific gravity	Particle size range
1.	Cement, OPC, 53-grade	3.15	31 µm – 7.5 µm
2.	Micro silica	2.2	5.3 µm – 1.8 µm
3.	Quartz powder	2.7	5.3 µm – 1.3 µm
4.	Sand	2.65	0.6mm – 0.3 mm
5.	Steel fibres	7.1	Length: 30 mm and diameter:0.4 mm
6.	River sand	2.61	2.36 mm – 0.15 mm

Table.2: RPC Mix Proportion

Material	Mix proportion			
	RPC	RPCS F1	RPCSF 2	RPCS F3
Cementitious material (cement=85%, silica fume=15%)	1	1	1	1
Fine aggregate (river sand)	1.02	1.02	1.02	1.02
Quartz powder	0.22	0.22	0.22	0.22
Steel fiber in %	-	0.5	1.0	1.5
Superplasticizer (sulfonated napthaleneformaldehyde) in %	4	4	4	4

- RPC= Plain RPC without steel fibers
- RPCSF1= RPC with 0.5% steel fiber
- RPCSF2= RPC with 1% steel fiber
  RPCSF3= RPC with 1.5% steel fiber

Table.3: Selection Parameter

COMPONENTS	SELECTION PARAMETER	FUNCTION	PARTICLE SIZE
Sand	Good hardness Readily available and low cost.	Gives strength	150 µm to 600 µm
Cement	C_3S: 60% C_2S: 22% C_3A: 3.8% C_4AF: 7.4%	Binding material, Production of primary hydrates	1 µm to 100 µm
Quartz powder	Fineness	Max. reactivity during heat-treating	5µm to 25µm
Silica fume	Very less quantity of impurities	Filling the voids, Enhance rheology, Production of secondary hydrates	0.1µm to 1µm
Steel fibers	Good aspect ratio	Improve ductility	Length 13mm to 25mm Dia. 0.15 – 0.2 mm
Super plasticizer	Less retarding characteristic	Reduce w/c	Polyacrylate based

VIII. MIXING SEQUENCE

An important factor for studying new cementitious materials is the mixing procedure (Geiker et al.,2007). This influence is often neglected and might bea source of error when analysing experimental results. Since RPC is composed of very fine materials, the conventional mixing method is not appropriate and mixing method cannot be the same.The following sequence in mixing RPC is based on some previous studies (Bonneau et al., 1997;Feylessoufi et al., 2001; Morin et al., 2002; Chan and Chu, 2004; Lee and Chisholm, 2005; Shaheen and Shrive, 2006), as well as trial-and-error approaches:

- Dry mixing powders (including cement, quartz sand, crushed quartz and silica fume) for about 3minutes with a low speed of about 140 rpm (1 minute at a constant speed of 1800 rpm if the high speed mixer is used). Addition of half volume of water containing half amount of superplasticizers.
- Mixing for about 3 minutes with a high speed of about 285 rpm (applicable to both types of mixers).
- Addition of the remaining water and superplasticizers.
- Mixing for about 10 minutes with a high speed of about 285 rpm (8 minutes at a constant speed of 1800 rpm if the high speed mixer is used).
- The whole mixing process takes about 12 to 16 minutes.

IX. MATERIAL SELECTION

9.1.Silica Fume

A highly reactive silica pozzolan is an essential component of reactive powder concrete, performing three vital roles for which it needs the following properties:

- It must be sufficiently fine to pack closely around the cement grains, improving the density of the composite matrix and minimizing the potential for voids between the particles.
- It should possess considerable pozzolanic activity, such that the non-cementing portlandite crystals [Ca (OH)] generated by hydration of the cement react with the silica to form additional C–S–H gel, reinforcing the binding of the composite. 3. The particles should have a basically spherical shape to act as a lubricant within the fresh mix, improving its ability to flow and be cast into moulds.

Conventionally, the reactive silica used for RPC has been silica fume, which is an industrial by- product of the manufacture and purification of silicon, zirconia and ferro-silicon alloys in submerged-arc electric furnaces. Escaping gaseous SiO oxidises and condensates as extremely fine (0.03 – 0.2 µm) spherical particles of amorphous silica, neatly fulfilling the requirements listed above. One of the potential drawbacks of RPC production in New Zealand is the absence of a domestic source of silica fume: importing this material is an expensive proposition, both because of high demand and an inconveniently light bulk density of 200 – 300 kg/m, complicating shipping and handling.

Fig.1: Silica fume

9.2 CEMENT

Due to the very high cement factor, the choice of cement can be an important factor in the performance of RPC. Based on published practice, the ideal cement has a high C3S and C2S (di- & tri-calcium silicate) content and very little C3A (tri-calcium aluminate). This is understandable because C3A has little intrinsic value as a binding agent and is primarily included in cement due to its role as a flux during the calcination process. Consequently, most RPC made with commercially-available cement employs an ASTM Type V,sulfate-resistant blend, which is formulated specifically for low C3A content

9.3.QUARTZ FINES

For RPC mixes designed to be cured at temperatures exceeding 90ºC, including autoclaving at elevated pressures, additional silica is necessary to modify the CaO/SiO ratio of the binder. In these cases powdered quartz flour with a mean particle size of 10 – 15 µm was employed..

9.4.FINE AGGREGATE

The majority of mixes were produced using high purity silica sand widely used for foundry casting and mould-making with a near mono-sized particle size distribution.

9.5.STEEL FIBERS

To enhance the RPC ductility, some mixes were produced with micro-fibres of straight carbon Steel wire, 13 mm in length and 0.2 mm in diameter, with a minimum on-the-wire tensile strength of 2,000 MPa.

9.5 SUPER-PLASTICISER

The very low w/b (cement + silica fume) ratios used in RPC are only possible because of the fluidizing power of high-quality third generation super-plasticizing agents. ViscoCrete-5 was selected as the most suitable for use. This is described as an aqueous modified carboxylate, designed specifically for ultra-high water reduction applications such as self-compacting concrete. To minimize any air-entrainment effects due to the high-dosage rates necessary, 1% Pronal 753S defaming agent, was also added to the super-plasticizer before us.

X. TESTS ON FRESH RPC MIX

10.1 Slump flow test

The slump flow is used to assess the horizontal free flow of SCC in the absence of obstructions. It was first developed in Japan for use in assessment of underwater concrete. The test method is based on the test method for determining the slump. The diameter of the concrete circle is a measure for the filling ability of the concrete

Table.4: slum and v-funnel values

Test type	Water cement ratio	% of superplasticizer	Limits (standards)	Achieved values
Slump flow test	0.34	4%	650-850mm	690mm
v-funnel test	0.34	4%	14-44 seconds	42 seconds

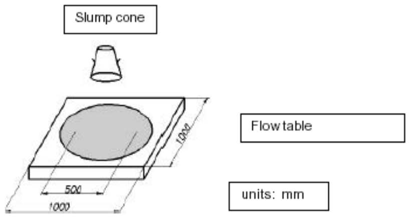


Fig.2: Slump Cone

10.2. V-Funnel Test

V-funnel test is used to determine the filling ability (flow ability) of the concrete.

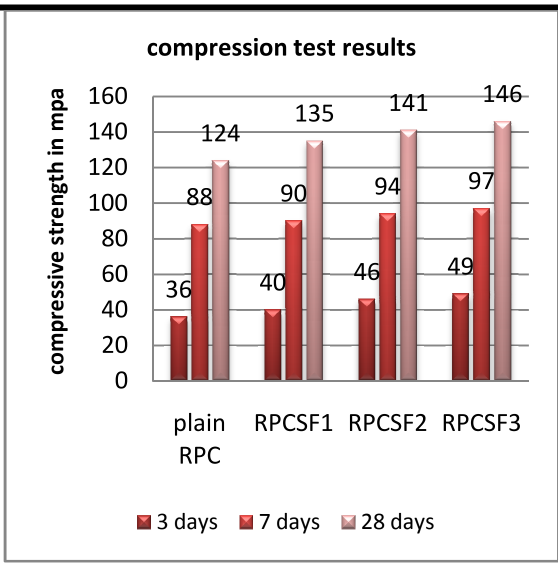
XI. TESTS ON HARDENED RPC

Once concrete has hardened it can be subjected to a wide range of tests to prove its ability to perform as planned or to discover its characteristics if its history is unknown. For new concrete this usually involves casting specimens from fresh concrete and testing them for various properties as the concrete matures. The 'concrete cube test' is the most familiar test and is used as the standard method of measuring compressive strength for quality control purposes. Concrete beam specimens are cast to test for flexural strength and cast cylinders can be used for tensile strength. Specimens for many other tests can be made at the same time to assess other properties,e.g.Drying shrinkage, thermal coefficient, modulus of elasticity.

11.1 COMPRESSION TEST

Table.5: Compression Test Result

No of days of curing	Plain RPC (Mpa)	RPC with 0.5% steel fibres (Mpa)	RPC with 1.0% steel fibres (Mpa)	RPC with 1.5% steel fibres (Mpa)
3 days	36	40	46	49
7 days	88	90	94	97
28 days	124	135	141	146



Graph1 Compressive Strength VS Number of days of curing

11.2. SPLIT TENSILE TEST

Table.6: Split Tensile Test Result

Time	Plain RPC	RPC with 0.5% steel fibres	RPC with 1.0% steel fibres	RPC with 1.5% steel fibres
3 days	3.8Mpa	4.1Mpa	4.4Mpa	5Mpa
7 days	7.2Mpa	8.7Mpa	9.1Mpa	9.6Mpa
28 days	9.1Mpa	9.7Mpa	10.1Mpa	10.6Mpa

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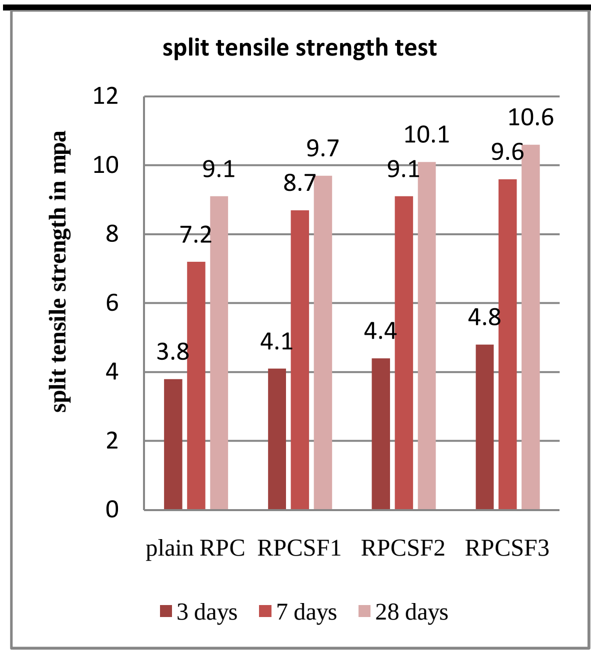
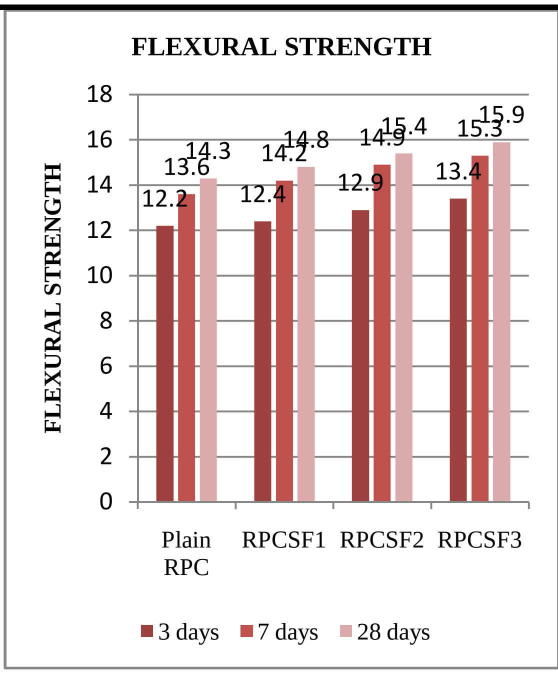


Graph 2 Split Tensile Strength VS Number of days of curing

11.3.Flexural Strength Test

Table.7: Flexural Strength Test Results

No of Days of curing	Plain RPC (Mpa)	RPC with .5% steel fibres (Mpa)	RPC with 1% steel fibres (Mpa)	RPC with 1.5% steel fibres (Mpa)
3 days	12.2	12.4	12.9	13.4
7 days	13.6	14.2	14.9	15.3
28 days	14.3	14.8	15.4	15.9



Graph 3 Flexural Strength VS Number of days of curing

XII. APPLICATIONS OF RPC

• RPC's properties, especially its high strength characteristic suggests the material might be good for things needing lower structural weight, greater structural spans, and even in seismic regions, it outperforms normal concrete. Below are a few examples of real-world applications, though the future possibilities are endless.

• First bridge that used RPC was a pedestrian bridge in Sherbrooke, Quebec, Canada. (33,000 psi ~230MPa) It was used during the early days of RPC production. Has prompted bridge building in North America, Europe, Australia, and Asia.

• Portugal has used it for seawall anchors

• Australia has used it in a vehicular bridge

• France has used it in building power plants

• Qinghai-Tibet Railway Bridge

• Shawnessy Light Rail Transit Station

• Basically, structures needing light and thin components, things like roofs for stadiums, long bridge spans, and anything that needs extra safety or security such as blast resistant structures

XIII. 13.RESULT &DISCUSSION

- Addition of steel fiber at particular volume fraction is found not to affect the workability of RPC. RPC is easily mixed with steel fibers, although while casting some of the samples, workability of RSFRPC mix can be improved by using lower percentage of fibers.
- Addition of steel fibers does not affect the finishibility of RPC outer surface of concrete after casting was as smooth as plain RPC.

- Marginal increase in bulk density and marginal decrease of flow of concrete was observed due to addition of steel.
- Ultimate compressive strength of SFRPC is 30% higher may be because of more confined and dense concrete.
- Improved by readjusting the doses of plasticizers more workable concrete can be obtained and strength can be improved. This is very obvious as compressive strength of RPC is primarily affected by the property of matrix and not due to the influence of the fibers.
- Split tensile strength of RPC with steel fiber in comparison to plain RPC is found 50% more respectively addition of fibers is significantly affecting the splitting tensile strength.
- Under four point loading arrangement used for flexural strength testing, the failure occurs in middle third portion of the specimen, in case of plain RPC, failure is sudden, without show in the first cracking load. While in the case of RPC with steel fiber beam, the first crack could be seen easily .Cracks start slowly from the bottom layer of the specimen and as the load increases, the crack propagates up to the top layer of the specimen.
- Flexural strength of RPC with steel fiber in comparison to the plain RPC is found to be 60% higher respectively. Here addition of fibers significantly increases the flexural strength of RPC.
- Steel fiber contained RPC specimens failed in ductile manner under static loading because of the effective bridging action of fibers across the tensile cracks. Thus it can be assumed that the structural components made of FRPC would give ample warning before the failure, which is never expected for plain RPC.

XIV. CONCLUSION

The above experimental program leads to emphasize the effects of steel fibre on properties of fresh and hardened steel fiber reinforced ultra high performance concrete. It is observed from the results that the presence of steel fiber increases the overall performance of the ultra high performance concrete. The enhancement in engineering properties has clearly shown in all the above mentioned experiments. Basically the superiority of the self-compacting concrete mainly lies in the strength and durability characteristics of the ultra high performance concrete mixture. The main objective of the present investigation was to study the behavior of steel fiber reinforced self compacting ultra high performance concrete under loading. Preliminary investigation was also conducted to arrive at an optimum dosage rate of steel fibers. The fresh and hardened properties of SFRPSCC specimens were also studied and compared the results with that of ordinary ultra high performance self compacting concrete. The conclusions of the present investigation and the scope for the future work are presented in this paper. Addition of steel fibers has increased ultimate load than that of conventional RPSCC beams under flexure.

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