CHAPTER-II

REVIEW OF LITERATURE

2.0 GENERAL

Review of papers has been conducted on the mix proportion, mechanical and durability properties of Reactive Powder Concrete (RPC). 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.

2.1 RPC – MIX PROPORTIONS

Dattatreya. J.K., et al., (2007)\textsuperscript{20} 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.

Dili and Manu Santhanam (2005)\textsuperscript{24} developed two RPC mixes of 200MPa and 800MPa strength, which could be suitable for nuclear waste containment structures. The workability and durability properties were studied for the designed RPC mix. Also characterization
of mechanical properties was carried out. The durability test carried out for the RPC mixes showed that the flow table test as per ASTM C 109 was in the range of 120%-140% and the water and chloride ion Permeability is extremely low. These test results indicates the suitability of the designed RPC mix for nuclear waste containment structures. However, the suitability of RPC mix for use in nuclear waste containment structures with respect to resistance then penetration of heavy metals and other toxic wastes emanating from nuclear plants has to studied

Masami Uzawa, et al., (2005) explored the practical applications of the reactive powder concrete with steel fibres with a high compressive strength of 200 MPa. Masami Uzama improved the already existing Reactive Powder Concrete (RPC) and a new material was proposed with simple curing process. This reactive powder composite material (RPCM) has high compressive strength and toughness inspite of simple curing techniques unlike RPC. This RPCM premix consists of (steel fibre reinforced ultra high strength mortar) cement, siliceous material quartz sand, special water reducer and high strength steel fibre (0.2mm diameter and 15mm length). The results showed that the RPCM has an extremely high fluidity and thus excellent self-compactability in the state of fresh mortar and when it is hardened, it had high levels of strength and toughness with a compressive strength of about 200 N/mm^2.

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.

**Stephanie Staquet and Bernard Espion (2002)** studied the mechanical properties of Reactive Powder Concrete made with the materials available in Belgium. Also, it was suggested that the CEM152.5 which was used in RPC applications can be replaced by VEM 42.5 to obtain a compressive strength of 180MPa without heat treatment. The workability of the concrete made with the white silica fume from the Zirconium industry and the light grey silica fume from the silicium industry had better workability than the RPC’s made by white and black silica fume from silicium industry.

**Richard and Cheyrezy (1995)** developed an ultra high strength ductile concrete with the basic principles of enhancing the homogeneity by eliminating the coarse aggregate and enhancing the microstructure by post-set heat treatment. In addition, the ductility and tensile strength of concrete is increased by incorporating small, straight, high tensile microfibres. Two types of concretes are developed and designated as RPC 200 and RPC 800. These concretes had exceptional mechanical properties, which resulted in elimination of reinforcement, and reduction of materials resulting in reduction of self-weight resulting in cost savings. The concrete finds its applications in industrial and nuclear waste storage silos.
2.2 RPC – NON-DESTRUCTIVE TESTS

Glenn Waher, et al., (2004)\textsuperscript{32} conducted non-destructive tests on reactive powder concrete (RPC) 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 modulii 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 modulii of elasticity.

2.3 RPC – DURABILITY PROPERTIES

Harish.K.V., et al.,(2008)\textsuperscript{36} 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.

Dattatreya.J.K., et al., (2008)\textsuperscript{21} developed a mix proportion for RPC concrete and various durability test procedures suggested by other scientists for RPC were discussed in this paper. Also, the various
testing procedures for finding the mechanical and durability properties of RPC have been identified. It is found that RPC is very sensitive to heat treatment and a slight change in curing regime affects the strength of RPC

Cwirzen.A. (2007) studied the influence of curing regime on the mechanical properties of ultra high performance concrete. Nine different curing methods were tried with variation in heat treatment, variation in water to binder ratio, with variation of filler materials like silica fume and fine quartz. The microstructure of the specimens was investigated by electron microscope and mercury intrusion porosimeter scan. Results revealed that increase in heat treatment periods decreases the hydration processes and refine the microstructure. This results in higher compressive strength. The scanning electron microscope investigation revealed the formation of one hydration rim around anhydrous cement particles and the presence of a hollow shell in all investigated specimens

Halit Yazici (2007) developed an Ultra high performance concrete by combining pulverized fly ash (FA), pulverized granulated blast furnace slag (PS) and silica fume (SF) with the portland cement (PC). PC was replaced with FA and PS at specified ratios. Basalt and quartz powder were used as an aggregate in the mixtures. Three different curing methods (Standard, autoclave and steam curing) were applied to the specimens. Test results indicated that high strength concrete could be obtained with high volume mineral admixtures. Compressive strength of these mixtures is over 170 MPa.
Saremi.M. and Mahallati.E., (2002) studied the chloride ion passivity by simulated concrete pore (SCP) solution using electrochemical techniques. The sensitivity of cyclic potentiodynamic parameters and impedance parameters were investigated. The objective of the present study was to study the effect C1- ion concentration on the stability of passive file on mild steel in Simulated concrete pore (SPC) solution. The study was done to understand the effects on anodic inhibitors on passive film performance.

Morin.V., et.al., (2002) studied the capillary network of RPC by ultrasonic and autogeneous shrinkage measurements. The evaluation of the activation of different modes during hydration processes was performed. Segmentation of sedimentary pores occurs because of the segmentation of capillary network because of chemical activity induced in C-S-H chains. This study of the capillary network is crucial because it provides information about the porosity evolution, which is an important parameter in the transport properties of the concrete, which are related to its durability.

Matte.V., Moranville.M., (2000) conducted tests to predict the long – term durability of RPC, the hydration rate of cement minerals, pozzolanic reactivity of silica fume, pore structure and mechanism of chemical reactions. So first, the microstructure of RPC matrix was simulated using the NIST micro structural model. Then the transfer of Ca ions through percolating water was estimated using DIFFU-Ca, a model based on the local chemical equilibrium. This double modeling validates the damage process related to an instantaneous dissolution of
anhydrous cement silicates at the degradation from which results in a higher connected pore, space and is in good agreement with experimental results. The study reveals that the RPC matrix is durable as long as a sound zone persists. Considering only the calcium concentration, the degraded depth was 14-15 mm at 300 years for the RPC matrix, in experimental conditions of leaching. This value could be taken into account to determine the thickness of high integrity containers to be used in the storage of type B nuclear waste without cementation.

Matte.V. et al. (1999) studied the RPC which was a class of concrete which possesses a high silica fume content (25% of the total binder material) and a very low water cement ratio (0.20) The heat treatment process applied after demoulding, at temperatures between 20°C to 400°C for enhancing the hydration and pozzolanic reactions. This process improves the mechanical and micro structural properties. A compressive strength of 200MPa and 800MPa was achieved by adding steel fibres, which in turn improves the ductility of concrete.

Roux.N., et al., (1998) studied the durability properties of RPC by measuring porosity air permeability, water absorption, diffusion, and migration of chloride ions, accelerated carbonation, resistance to reinforcement corrosion, resistivity and resistance to mechanical abrasion. The fundamental experimental results obtained on RPC 200 were, the absence of pores with diameters exceeding 15mm, an air permeability coefficient of $2.5 \times 10^{-18}$ m$^2$, following exposure to severe drying conditions (30 days at 80°C). Extremely low water absorption,
an effective diffusion coefficient - 50 times less than that of low cement concretes no carbonation after exposure to 5% CO$_2$ for 42 days (60% relative humidity) and to 100% CO$_2$ for 90 days. A reinforcement corrosion rate lower than 0.01 µm/yr (corrosion threshold = 1 µm/yr) a resistivity of RPC 200’s cement – based matrix 70 times higher than that of C30 concrete and an abrasion coefficient comparable to that of a mortar cast with a corundum aggregate

The durability properties of a new cement based materials with excellent micro structural properties were studied. The durability properties were studied for the concrete. Study of the C-S-H (behavior of hydrates) gel was studied on a pure cement and silica fume paste. The advantage of silica fume addition on calcium leaching was studied by XRD analysis from SEM observations and from the tritium diffusion and pore distribution analysis. It was found that the leaching greatly affects the microstructure especially that of the anhydrous cement grains remaining in the paste.

**Vodak.E. et al.,(1997)** conducted experiments to determine the thermal characteristics of RPC concrete like thermal conductivity, thermal diffusivity and linear thermal expansion coefficient of RPC. The concrete used in French nuclear power plant were tested for a temperature Range of 20°C to 200°C, specific heat of -30°C to 100°C, moisture diffusivity from 0 to 75% of maximum water saturation at room temperature and water vapor diffusivity at room temperature. The results were compared with the measurements of other authors for
concretes with similar composition show a reasonable agreement for most of the parameters.

**Feylessoufi.A. et al.,(1997)** discuss results of specimens cured with three different heating modes. The results confirmed the formation of Xonolite when heat-treated and the data showed that the kinetically controlled thermal curing had a control on hydration and crystallization.

**Feylessoufi.A., et al,(1996)** studied a Reactive Powder Concrete (RPC) with a compressive strength of 230 MPa with low temperature nitrogen adsorption – desorption volumetry by DRIFTS(Diffuse Reflectance infrared Fourier Transformed Spectroscopy). From the experiments conducted, it was observed that RPC had an open network of pores of various diameters with high level durability characteristics.

**Helene Zanni, et al.,(1996)** studied the hydration and pozzolanic reaction by two RPC specimens with two different heat treatment at 20°C and 250°C. The aim of the experiment was to investigate the effect of temperature on hydration and pozzolanic activity. At 250°C microstructural changes leads to the occurrence of Q³ peak attributed to the formation of Xonolite.. The heat treatment led to the increase in the C-S-H chain length due to the pozzolanic activity of silica fume and quartz powder.

It was found that the leaching greatly affects the microstructure especially that of the unhydrous cement grains remaining in the paste
2.4 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.

Toshiyuki Kanakubo (2006)\(^{80}\) reported the findings of JCI technical committee sponsored round robin test program on tensile characteristics of ductile FRCs (DFRCs) in which four types of uniaxial direct tension tests were evaluated using different types /dimensions of specimen and loading jigs. Flexural and split tension tests were also evaluated. In general, differences were observed in the results reported according to testing method, specimen parameters, shape and dimensions, boundary conditions and specimen preparation.

Katrin Habel, et al., (2006)\(^{46}\) studied the improved performance of ultra high performance fibre-reinforced (UHPFRC) concretes with fibre cocktail. This study revealed that the small fibres were contributing the strain hardening resulting in bridging of micro cracks and long fibres were responsible for transferring of forces in localized cracks and govern the softening part. So the improved UHPFRC resulted in higher stiffness and higher resistance to cracking with a hardening modulus of more than 45GPa preventing softening behavior.

Graybeal.B., (2006)\(^{9}\) has reported direct tensile strength determination of UHPC using briquette specimens conforming to AASHTO T132, which consist of dog bone-shaped briquette is 76 mm long with 25 mm square cross section at middle length. Special self-aligning grips allow for passive gripping of the specimen in the test machine and ensure uniform loading. The first crack strength ranged from 6.3 MPa to 10.1 MPa while the post cracking strength ranged from
5.6 to 9.5 MPa. The toughness expressed as the ratio of post peak to pre-peak areas ranged from 2 to 5.5. In majority of the cases, strain-hardening characteristic was not evident.

**Dario Redaelli (2006)** studied the mechanical behavior of real scale UHPFRC ties with reinforced steel bars. It is proved that fibres improved the ductility of concrete when the volume of fibre is more than 1.5%. However, at the ultimate limit state, even a large amount of additional ordinary reinforcement cannot avoid strain localization and a brittle failure. This study revealed that UHPFRC tensile members cannot be made fully ductile by introducing ordinary reinforcement and an alternative definition of the amount of minimum reinforcement to avoid brittle failure or UHPFRC tensile members had been proposed.

**Dili and Manu Santhanam (2005)** developed two RPC mixes and designated as RPC 200 and RPC 800 which could be suitable for nuclear waste containment structures. The mixes were tested for its workability, mechanical and durability properties. The flow table test as per **ASTMC 109** was in the range of 120%-140% and the water and chloride ion permeability is extremely low indicating the suitability of nuclear waste containment structures. However, RPC needs to be suitable with respect to resistance to penetration of heavy metals and other toxic wastes emanating from nuclear plants to qualify for use in nuclear waste containment structures.

**Dean Bierwagen, et al., (2005)** in a multi-phase project tested a 71 ft (21.64m) long RPC test beam for shear and flexural capacities. In phase II 111 ft (33.83m) long beams were cast and tested. Based on the
test results the section of web was reduced in top flange by one inch (25mm) and bottom flange by two inches (50mm). The design guidelines were taken from the recommendations available from the reports available as France and the construction was completed in 2005.

**Jorg Jungwirth, et al.,(2004)** performed material tests and tests on structural members of RPC with reinforcement bars. In order to understand the behavior of structural members in UHPC, large-scale tests simulating the condition in actual structures were carried out. Three specimens with different reinforcement ratios between 1 % and 4.8 % (ribbed steel, $f_y = 556$ MPa) were tested. The dimensions of the specimens were 160 x 160 x 1500 mm. The strain was measured over a gauge length of 1000 mm. Due to the presence of fibres and their contribution, the behavior in tension in UHPC shows a drastic difference when compared to that of ordinary concrete. This has an important influence on the design of structures in UHPC

**Resplendino.J.(2004)** in his report on the first recommendations for UHPC observed that the post peak behavior of UHPC is quite difficult to characterize because it depends very much on the mixing and placement process Any flow during concrete placing tends to align fibres in the direction of flow.

Fibres close to walls are naturally aligned parallel to the formwork. This phenomenon ceases beyond a distance from the formwork in excess of the fibre length. The closer component thicknesses are to the length of fibres, the greater is the effect on the effective tensile strength of the parts, Preferential gravitational orientation of fibres can
sometimes occur, due to the natural behavior of fibres in the viscous-liquid phase of concrete before it sets.

**Reineck and Greiner (2004)** carried out Tensile tests on Ductal, a commercially available formulation of Reactive powder concrete (RPC) with 2% volume of steel fibres. They obtained the compressive strength values of about 180 MPa and axial tensile strength of about 9 to 10 MPa for RPC. These values comply well with the results published by other researchers.

**Behloul and Lee (2004)** reported a characteristic tensile strength of 8 MPa and a post-peak strength of 5 MPa for the RPC mix (Ductal) used for the Seonyu Bridge in Seoul. The axial tensile tests were carried out with flat bone-shaped specimen with a cross section of 30 x 90 mm. This shape is better suited than prisms or cylinders to determine this important material characteristic for UHPFRC used for shells and tanks.

**Karl-Heinz (2004)** conducted direct tension tests, and reported only a slight increase of the load after first cracking. Mostly a decrease of the load occurred, and in some cases, it was so drastic that it obviously was a specimen with a weak cross section where the fibres were mostly orientated perpendicularly to the load direction during concreting. Therefore, utmost care must be paid on the concreting and the quality assurance in general. For the flexural tensile strength of 25 to 40 MPa were reported. These values were conformed in own tests, but the flexural tensile strength clearly decreases with increasing depths of the prisms, and this means that there was a distinct "size
effect”. Therefore, the size of the prism must always be mentioned when such value are reported. One main cause for this size effect was the orientation of the fibres, which lead to a preferred orientation of the fibres parallel to the surface respectively to the formwork, and this has greater influence for small dimensions.

Teutsch, et al.,(2004) observed a ductile fracture behavior in UHPC mixtures with short fibres. Compared to unreinforced UHPC mixtures, the tensile tests showed that addition of short discontinuous fibres leads to a change in loading capacity and fracture behavior. A higher service load and a continuous load carrying behavior due to a finely distributed crack development were observed, i.e. higher loads were achieved at same displacements. The changes in the matrix composition of the UHPC mixtures (no short fibres) probably do not influence the bonding characteristic significantly and hence no significant differences in the progression of the load-displacement curves obtained by the tensile tests were observed.

Dallaire, et al.,(1998) describes the various mechanical properties of the material(RPC) used to construct Sherbrooke pedestrian Bikeway bridge in this paper. Ductility of RPC is improved by adding fibres (1.8% of volume, 12mm long) or confining the material in a steel tube. The bottom chord members of bridge consist of two 320X380 mm prestressed beams with boxes every 5m that correspond to the connection between the diagonals and the bottom beams. The elimination of reinforcement in RPC structures leads to freedom in shape and form of the member. So It is concluded that this material
can be used in thin-walled pressure and sewer pipe, in tunnel wall and ceiling panels and in other projects that need high strength and ductility requirements.

Collerpardi. S., et al., (1998)\textsuperscript{14} compared the mechanical properties of original reactive powder concrete with the modified reactive powder concrete (with the coarse aggregate addition). In modified RPC graded natural aggregate (max. Size 8mm) was used to replace the fine sand and part of the cementitious binder. Both the original and modified RPC performed better in terms of high strength and lower drying shrinkage or creep strain when they are steam cured rather than cured at room temperature. Also a denser microstructure of cement matrix is achieved for RPC specimens steam cured at 160°C.

Ashish Dubey, et al., (1998)\textsuperscript{7} studied the post-peak energy dissipation mechanism across a crack. It was revealed that the energy dissipation is due to the pull-out of fibres across the crack. Addition of pozzolanic materials like silica fume increases the brittleness of the matrices. Increase in load results in crushing and splitting of matrix, which in turn curtail the ability of fibres to transfer the stresses. In addition, it was suggested that the toughness of RPC can be improved by adding high-reactivity metakaolin to the mix which will in turn improve the durability properties of RPC.

Surendra P. Shah, et al., (1998)\textsuperscript{76} in this report outline existing procedures for specimen preparation in general and discusses testing, workability, flexural strength, toughness and energy absorption. Newly developed test methods are presented for the first time for impact
strength and flexural toughness. The applicability of the following tests to fibre reinforced concrete (FRC) are reviewed: air content, yield, unit weight, compressive strength, splitting tensile strength, freeze–thaw resistance, shrinkage, creep, modulus of elasticity, cavitations, erosion and abrasion resistance. The report applies to conventionally mixed and placed fibre reinforced concrete (FRC) or fibre reinforced shotcrete (FRS) using steel, glass, polymeric and natural fibres.

Olivier Bonneau and Mohamed Lachemi, (1997) at a precast plant in Sherbrooke University, produced two Reactive powder concretes (RPC). One was a ready mix RPC and another was used in precast plant. In ready mix RPC samples were prepared both with and without fibres. All these RPC samples were tested for compressive strength, modulus of elasticity freezing and thawing cycling resistance, scaling resistance to deicing salts and resistance to chloride ion penetration. The results show that the RPC mix were found to be freeze-thaw resistance and loss of very low mass under the scaling test. Chloride ion penetration was below 10 coulombs for RPC impregnated with steel fibres.

Luigi Bioizi, Gian Luca Guerrini and Rosati (1997) studied the effect of high tensile steel micro fibre on high strength concrete on compression and tension under controlled strain through closed-loop system. The maximum size of aggregate used was 3mm with aggregate binder ratio of 2, and water to binder ratio was 0.2mm. The effect of different dosages of fibre on concrete was evaluated. Also it was
concluded that poly acrylic based superplasticizer gives materials with lower porosity.

Aftab.A.Mufti, (1992) studied the suitability of fibre-reinforced concrete deck slabs without steel reinforcement. Four half-scale models were developed for slab-girder bridges with polypropylene fibres completely avoiding steel reinforcement and related corrosion problems. To avoid the deck slab arching on the upper surface, the upper flange of girders should be connected with steel straps in transverse directions. This has been simulated by introducing stiffeners along the edges using unconventional edge beams. The tested results proved that slab had major flexural rigidities in horizontal plane and it was recommended to introduce shear connectors to ensure an effective transfer of in-plane forces from the deck slab to the girders.

2.5 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.

Almansour.H. and Lounis.Z.(2008) developed an UHPC with high strength and very low permeability for construction of long life bridges. The existing design recommendations for UHPC was made use of and
designed according to the Canadian Highway Bridge Design Code. Results obtained indicate there is a significant reduction in concrete volume by 49%-65%.

**Kim Huy Hoang, et al.(2008)** studied the mechanical properties of UHPC with two types of steel fibres (L_f/d_f=17/0.2,35/0.5) The combination of fibres resulted in good flowability, flexural strength and compressive strength of over 150MPa. Also it was observed that the higher strength was attained due to micro steel fibres and a dosage of not less than 1% is recommended. Also the ratio of silica fume and other filling powders should approximately be 0.2 – 0.25 for manufacturing the self-compacting ultra high strength concrete with water-binder ratio of 0.2

**Naaman.A.E. (2008)** suggested the use of the nomenclature “High Performance Fibre Reinforced Composites”(HPFRC) describing them as having a combination of high strength and toughness-ductility. In 1987 paper presented at an IABSE conference in Paris, Naaman described the typical tensile response of strain-hardening FRC composites, and provided a theoretical formulation to achieve strain-hardening behavior. The terms ‘strain-hardening’ and ‘strain-softening’ were not used but instead the terms “high performance” and conventional fibre reinforced concrete were used.

**Marko Orgass and Yuette Klug (2004)** researched the influence of short and a cocktail of short and long fibres on the mechanical properties especially on the ductility and size effect of UHPC. The experiments were conducted for specimens of various fibre dosages
ranging from 0, 1, 2 % and varying the grain size from 0.8mm for RPC to 5.0mm for UHPC. The flexural strength and crack behavior represented that there is an increase in strength with increase in volume of steel fibre and ductile post fracture behavior was observed for 2% volume of the fibre.

*Jungwith.J. and Muttoni.A.,(2004)* studied the tensile behaviour of UHPC members at Structural concrete laboratory. The behavior was different due to the presence of high strength steel fibres. Also it was observed that the stiffness of the element was very high due to the very high bond and tensile strength. Also Jungwirth recommended UHPC with pre-stressing cables or reinforcement to carry the major tensile stresses.

*Rossi.P. and Parant.E.(2001)* developed a new Ultra high performance(UHPC) material and wanted to characterize the same by the gradual and continuous activation of the multiscale fibres, until the peak strength was reached. In addition, the studied material is modeled as an elasto-plastic specimen with strain hardening in tension. The results show the material is very sensitive to rate of loading and the modulus of rupture increases by 25% in the range of quasi-static loading.

### 2.6 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.

Zhang.M.H., et al.,(2006) developed a new engineered cementitious composites (ECC) impregnated with poly vinyl alcohol. This had a high ductility feature which can be used in repair and retrofit of existing structures. The specimens were tested for high early strength gain rate with various combinations of binder system. The micromechanical model revealed that the quick deterioration in strain capacity which was due to rapid drop of complementary energy and continuous rise of crack tip toughness. Initial flexural strength was 10MPa (4 hours) and improved to 16MPa at a later stage.

Masami Uzawa.M. et al.,(2005) explored the practical applications of the reactive powder concrete with steel fibres with a high compressive strength of 200 MPa. Masami Uzama improved the already existing Reactive Powder Concrete (RPC) and a new material was proposed with simple curing process. This reactive powder composite material (RPCM) has high compressive strength and toughness in spite of simple curing techniques unlike RPC. This RPCM premix consists of (steel fibre reinforced ultra high strength mortar) cement, siliceous material, quartz sand, special water reducer and high strength steel fibre (0.2mm diameter and 15mm length). The results showed that the RPCM has an extremely high fluidity and thus excellent self-compactability in the state of fresh mortar and when it is hardened, it had high levels of
strength and toughness with a compressive strength of about 200 N/mm².

Ming-Gen Lee, et al., (2005) studied the usage of RPC concrete as repair material and evaluated its bond and durability properties with existing High strength (HSM) and reinforced concrete (RC). The compressive strength, bond strength, steel pull out strength and relative dynamic modulus of elasticity (NDT) tests were carried out. The test result proved the superiority of RPC with respect to other concretes. The mechanical properties are 200% more when compared to the normal strength concrete. The results of slant shear tests show that the bond strength of RC/RC, HSM/RC and RPC/RC decreased significantly more with freeze–thaw cycles as compared with that of RPC/RPC.

Donnaes and Philippe (1998) developed Reactive powder concrete (RPC) in research laboratory at Bouygues, France. This concrete is composed of extremely fine powders of sand, cement, quartz, and silica fume. A new pedestrian walkway bridge was constructed in Sherbrooke, Quebec on November 27, 1997. This prefabricated 197ft walkway was constructed using prefabricated RPC structural elements. An innovation introduced in the assemblages which allowed in each cable a single strand and anchorage head was simplified by elimination of support plates since RPC can directly take the compressive stress developed during prestressing. Also a 2,150 sq.ft., façade for a Paris school was constructed using RPC. The façade
demonstrated the materials aesthetic qualities creating plates with an untreated surface similar to polished concrete

2.7 RPC-STUDIES ON INFILLED TUBES

Xiao.Y. and Chin.C.S.(2004)\textsuperscript{84} in his paper examines a numerical program to analyze the behavior of the concrete filled steel tubular (CFT) stub columns, and predict various modes of lateral interactions between steel tube and filled-in-concrete under axial compression. The behavior of CFT columns is controlled by both the strength and the confinement effect of steel tube and filled-in-concrete in the columns. Various lateral interactions between steel tube and filled-in-concrete in CFT columns are classified into eight different cases by the contact between steel tube and filled-in concrete at different stages.

Gupta et al., (2007)\textsuperscript{33} presented an experimental and computational study on the behavior of circular concentrically loaded concrete filled steel tube columns till failure. It was for investigating the effect of diameter and diameter to thickness ratio of a steel tube on the load carrying capacity of the concrete filled tubular columns. The effect of the grade of concrete and volume of flyash in concrete was investigated. The effect of these parameters on the confinement of the concrete core was also studied. Strength results of CFT columns were compared with the corresponding findings of the available literature. Several aspects from these studies are worth noting.
i) The CFT columns, fail essentially by local buckling, as the concrete strength increases the confinement effect of the concrete core decreases.

ii) The initial slope of the load–deformation curves obtained by the analytical model is found to be greater than that of the experimental one.

iii) In the analytical model, the deformation of the CFT specimens at the yield point is about 2–3 mm (about 20%–30%) less than their experimental counterparts.

Giakoumelis G. et al., (2004) studied the behavior of circular concrete-filled steel tubes (CFT) with various concrete strengths under axial loads. The effects of steel tube thickness, the bond strength between the concrete and the steel tube, and the confinement of concrete are examined. Measured column strengths are compared with the values predicted by Eurocode 4, Australian Standards and American Codes. All three codes predicted lower values than that measured during the experiments.

Lakshmi B. et al., (2002) conducted study on the effects of local buckling, bond strength, seismic loading, confinement of concrete and secondary stresses on the behavior of hollow steel tube and steel–concrete composite columns. Experiments were conducted both encased and in-filled composite columns tested by various researchers with a view to establish their behaviour and load-carrying capacity. The tests were conducted on two (14 m) long, (0.33m) diameter pipe columns, one empty and the other filled with concrete. It was
concluded that infilled concrete increases the load and moment carrying capacity without increasing the size of the column.

**O’Shea and Bridge (2000)** tried to estimate the strength of CFTs under different loading conditions with small eccentricities. All the specimens were short with a length-to-diameter ratio of 3.5 and a diameter thickness ratio between 60 and 220. The internal concrete had a compressive strength of 50, 80 and 120 MPa. From those experiments, O’Shea and Bridge concluded that the degree of confinement offered by a thin-walled circular steel tube to the internal concrete is dependent upon the loading condition. The greatest concrete confinement occurs for axially loaded thin-walled steel with only the concrete being loaded and the steel tube used as pure circumferential restraint. Eurocode 4 has been shown to provide the best method for estimating the strength of circular CFTs with the concrete and steel loaded simultaneously.

**Kilpatrick. A. et al., (1997)** examined the applicability of the Eurocode 4 for design of CFTs which use high-strength concrete and compare 146 columns from six different investigations with Eurocode 4. The concrete strength of the columns ranged from 23 to 103 MPa. The mean ratio of measured/predicted column strength was 1.10 with a standard deviation of 0.13. The Eurocode safely predicted the failure load in 73% of the columns analyzed.
2.8 RPC CONSTITUTIVE MODELING

Padmarajaiah.S.K. and Ananth Ramaswamy (2002) used three dimensional non linear finite element analysis to analyze the prestressed beams in flexure. An Ansys 5.5 version was used to simulate the analysis for fully and partially prestressed fibre reinforced beams. The fibre content was modeled explicitly since the fibre was expected to sustain the applied loads across the crack interfaces by their bridging action. The results correlated well with the experimental results and the crack pattern also matched well with the real specimen.

Yip.W.K.(1998) reviewed the generic form of equations for the constitutive stress-strain relationship of different grades of concrete at monotonic uniaxial compression. Numerous mathematical equations for the non-linear constitutive stress-strain relationship of concrete under uniaxial compression have been developed various investigators. An experimental investigation has been conducted to verify the use of these generic forms of equations in representing the ascending branch of the stress-strain relationship of various grades of concrete.

Sankarasubramanian.G. and Rajasekaran.S.,(1996) proposed a nonlinear hypo elastic constitutive relation for plane and axisymmetric structures. Based on the Darwin and Pecknold equivalent uniaxial strain concept a model was proposed to analyze variety of structural engineering problems. This model was found suitable also for blast loading effects and time dependent deformations.
Peter H. Feenstra and Rene De Borst, (1995) proposed a model for concrete under biaxial stresses (both tension and compression) under monotonic loading conditions. The proposed model was more suitable for unreinforced concrete structures and for a reinforced concrete structures like shear wall.

2.9 BOOKS AND REPORT

Ivan Markovic (2006) in the 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.

Benjamin A. Grabeal (2005) studied the strength and durability characteristics of Ultra-High Performance Concrete that make it suitable for use of highway bridge structures. Prestressed highway bridge girders were cast from this material and tested under flexure and shear loadings. The testing of these AASHTO Type II girders containing no mild steel reinforcement indicated that UHPC, with its
internal passive fibre reinforcement. Based on this research, a basic structural design philosophy for bridge girder design is proposed

Lee.N.P. and Chisholm.D.H.(2005)\textsuperscript{50} Report on the RPC produced in the laboratory to study the effect of water to binder ratio, dosage of superplasticizer, curing regime and the effect of silica fume and quartz powder on the compressive and tensile behavior of concrete. The RPC tested had a maximum compressive strength of 200 MPa and Flexural strength of 15-20MPa. The mechanical properties examined are directly correlated to the particle packing of the fine reactive powders added to the concrete.

JianXin Ma and Marko Orgass (2004)\textsuperscript{41} in their project report studied two UHPC’s with and without Coarse Aggregate for autogeneous shrinkage and other mechanical properties. The autogeneous shrinkage of UHPC with coarse aggregates is about 60% of the RPC. In addition, the compressive strength showed no difference between the RPC with and without coarse aggregate.

Voo.J.Y.L., Foster.S.J. and Gilbert.R.I.(2003)\textsuperscript{83} studied the effect of large-scale girders failing in shear. The girders were cast using 150-170MPa steel fibre reinforced reactive powder concrete to carry shear stresses in thin webbed prestressed beams without shear reinforcement. Comparisons were made for crack patterns for the specimens with respect to quantity and types of concrete mix and types of fibres in concrete mix. Also, the shear beams were modeled using finite elements with a good correlation observed for the non-linear numerical model against the experimental data.
Voo.J.Y.L. and Foster.S.J.(2003) suggested a model named the
Variable Engagement Model, which is developed to describe the
behavior of randomly oriented discontinuous fibre reinforced
composites subject to uniaxial tension. Experimental verification
concluded that the model is not only capable of capturing the stress
versus crack opening displacement behavior of both plain and
deformed steel fibres in the pre and post-peak ranges but can also be
used to describe the tensile behavior of micro-synthetic fibre-concrete
where the fibres fracture under load.

ACI 544.1R-96(Reapproved)(2002) Report on Fibre Reinforced
Concrete was proposed by ACI Committee which was a comprehensive
review of all fundamental principle of FRC, a glossary of terms, a
description of fibre type, manufacturing method, mix proportioning
and mixing methods, installation practices, physical practices,
durability, design considerations, applications, and research needs.

ACI 544-3R (1993) Report gives the information on the current
technology in specifying, proportioning, mixing, placing, and finishing
of steel fibre reinforced concrete (SFRC). This report provides the
guidelines for mixing techniques to achieve uniform mixtures,
placement techniques to assure adequate compaction, and finishing
techniques to assure satisfactory surface textures. Different mix
proportions were tested and tabulated.

Roy.D.M. et al., (1993) This is a review paper on UHPC
especially dealing with Reactive Powder Concrete. The review was
carried out on different headings, on all aspects of reactive powder
concrete starting from mix proportion to design and applications of RPC. From the above studies, the following conclusions were made.

The optimization of binary, tertiary, quaternary and multi-component mixtures with suitable combinations increases the packing density. An increase of twenty to thirty percentage of compressive strength is achieved due to this optimization resulting in a denser RPC mix.

Silica in the mix decides the strength of the designed mix. The performance of silica sand is limited. It was also noted that there is a need for microstructural investigations for thorough studies in the area of autogenous shrinkage, leaching properties, quantification of the products formed due to cement hydration, pozzolanic reaction etc.,

ACI 544-2R (1988)³ Report on specimen preparation and testing of specimen for workability, flexural strength, toughness and energy consumption. Newly developed test methods were presented for air content, yield unit weight, compressive strength, splitting tensile strength, freeze-thaw resistance, shrinkage and creep, modulus of elasticity, cavitations, erosion, and abrasion resistance.

ACI 544-4R (1988)⁴ Report on design practices for fibre reinforced concrete and mortar using steel fibres is reviewed. Mechanical properties were discussed, design methods were presented, and typical applications are listed.
2.10 SUMMARY OF LITERATURE REVIEW

To summarize the review of research work on RPC the following observations are made.

1. Lot of research works were carried out for the production of RPC which is an UHPC, but very few studies precisely compares in detail their mechanical properties with RPC. RPC without fibre was very brittle and to make RPC ductile it is necessary to add fibre. The volume and aspect ratio of fibre to be added should be optimized.

2. Curing regime refers to the sequence of temperature and humidity conditions in which the specimen should be placed which improve the microstructure of the Specimen. A random or wrong curing regime or sudden exposure to extreme temperature may disrupt the formation of C-S-H gel resulting in poor mechanical properties.

3. Reactive Powder Concrete can be interpreted like a concrete(approximately mortar) with the incorporation of ‘reactive powder’ components to react chemically following casting i.e. the cement by conventional hydration, silica fume through pozzolanic reaction with the resulting calcium hydroxide and the quartz powder by providing dissolved silica for the formation of further C-S-H gel.

4. RPC material tests carried out on standard specimens gives an average value of 180 MPa with a tensile strength of 10MPa and a flexural strength of 27MPa to 40MPa. The results were well comply with results of most of the researchers.
5. RPC is mostly applied in bridge deck slabs and tried in other precast wall constructions. The application of RPC may be tried in structural assemblages and other precast structures especially in tension members.