CHAPTER IX
SUMMARY AND CONCLUSION

9.0 INTRODUCTION

Reactive Powder Concrete (RPC) is a new type of Ultra High Performance Concrete that exhibits properties of enhanced strength, durability, ductility and long term stability. The objective of this study was to investigate the mechanical properties of an RPC formulation developed using indigenous materials under compression, tension, shear and flexure and to explore its application to some typical structural components which can be used for structural members of building frames and space structures. The performance of the structural components, such as angle sections and infilled tubes were evaluated through various tests small-scale structural models of the components. The experimental results are verified by non-linear numerical finite element study using ANSYS package.

The studies have been carried out in four phases consisting of three experimental phases and one analytical phase. The experimental phases focused on determining the material characteristics of RPC and evaluating behavior of RPC structural components. Over 200 individual specimens were tested to determine the material characteristics of RPC. The tests determined the compressive, tensile and flexural strength and other parameters for various dosages of fibre. The stress-strain characteristics in direct tension and compression were determined and stress-strain models were formulated to define the complete stress-
strain curves under compression and tension from basic material characteristics. In the second phase of experimentation, angle sections of various heights with different dosages of micro steel fibres were tested for compression to explore the possibility to be used as the structural component in building frames and space frames. The specimens were also tested under flexural loading. The use of angle sections in a framed structure necessitates joining of strut and tie members and design of joints. However, the edge distance of the bolt holes and the permissible stresses are to be determined for the design of joints. In the second phase of experimentation the edge distance for bolted connections were optimized by conducting direct tension tests on bolted plates so that on site drilling and fastening can be explored. However, the tearing failure of the plates was found to be a limitation to this approach.

Although RPC has much higher tensile strength than conventional concrete, the tensile strength, as obtained in the second phase of the experimental study, is not adequate for its use as tie members. Therefore, the use of RPC structural sections like angle will have to be confined to compression and flexural members only. The alternate approach is to use infilled tubes, which are strong in compression and could be made to resist tensile forces by prestressing. Such an approach exploits the high compressive Strength of RPC and the design of prestressed components is more simple as anchorage zone reinforcement can be eliminated. To investigate the behavior of such
infilled tubes, steel tubes infilled with RPC of various fibre dosages were tested for compression.

In the fourth phase of the study, the structural behavior angle sections in compression and flexure using was modeled numerically using ANSYS finite element package considering the stress strain characteristics of RPC and the fibres and taking into account the bond-slip behavior at fibre-matrix interface using spring elements. The results of this analysis were compared with the experimental results for the tests and reasonable agreement was obtained indicating the validity of the approach.

The major conclusions drawn from study are presented in Section 9.1. A brief discussion of ongoing and potential future research topics follows in Section 9.2.

9.1 CONCLUSIONS

The following conclusions are drawn based on the research within the PhD-thesis.

9.1.1 Conclusions

The following conclusions focus on the overall body of work presented in this thesis.

1. RPC with compressive strength of more than 205 MPa (Cube Compressive Strength) can be produced using indigenously available materials using simple process techniques.

2. RPC displays significantly enhanced material properties when compared to normal and high performance concrete.
3. RPC is a viable substitute for normal concrete and HPC in structural components.

4. A fibre dosage of 2% 13mm was found to be the optimum fibre content in order to achieve the maximum enhancement in material properties without affecting the workability of concrete.

9.1.2 Material Characterization

The following conclusions focus on RPC material characterizations.

9.1.2. (a) Compression test on cylinders

1. The RPC mixes were proportioned to achieve target cylinder strength of about 160 MPa and actual the compressive strength ranged from 110 MPa for plain RPC to a maximum of 171.3 MPa for RPC with fibre.

2. The variation of elastic modulus is found to better follow a cube root law with compressive strength as recommended by Eurocode 2 rather than a square root law as recommended by most of the codes of practice.

3. The crack pattern shows formation of vertical cracks for lower percentage of small fibre reinforcement and diagonal cracks for higher percentages of fibre reinforcement.

4. Stress-strain models, which can predict the complete stress-strain behaviour in both the pre-peak and post-peak regime from the reinforcement index and the density ratio were formulated using the experimental data and were found to have good correlation with the experimental data.
9.1.2. (b) Flexural/Fracture Tests on Beams

1. Shorter fibres of 6mm were more effective in increasing the first crack stress compared to 13 mm fibres. However, the 13mm fibres were more effective in enhancing the peak stress.

2. The peak stress ranged from 19.8 MPa to 30.2 MPa for RPCs.

3. At CMOD as high as 3.5 mm (>L/100), the RFTS ranges from 5.77 MPa to 24.2 MPa for RPCs.

4. The toughness Index \( I_{100} \) ranges from 70.9 to 195.3 for RPCs, which indicates that the post peak energy absorption is nearly equal to or better than that of an ideal elasto-plastic material. This indicates the superior toughness of RPC.

5. The fracture energy computed up to a CMOD of 3.5mm ranged from 5.6 N/mm to 13 N/mm for RPCs.

9.1.2. (c) Tensile tests on Briquette’s Specimen

The fibres stiffen the RPC matrix at the uncracked sections and strengthen it at cracked sections by bridging action. Hence, the composite load-deformation response is significantly improved in terms of axial load-carrying capacity as well as ductility. It leads to improvements in crack control.

1. The peak tensile stress ranged from 4.18 MPa for plain RPC to 12.44 MPa for mixed fibre ratios of 3% (1%6mm+2%13mm) whereas for 2% 13mm fibre the maximum tensile stress is 9.42MPa.

2. The strain at peak load varied from 250 to 13400 micro strains, which demonstrates the tremendous advantage offered by fibre
incorporation and the strain-hardening feature of HPFRC, especially for volume fractions of 2% and more.

3 Stress-strain models, which can predict the complete stress-strain behaviour in uniaxial tension in both the pre-peak and post-peak regime from the reinforcement index and the density ratio were formulated using the experimental data and were found to have good correlation with the experimental data.

9.1.2.(d) Double Shear Test using Beam Specimens

1 The minimum shear stress is 8MPa for RPC beam without fibre. Also with the increase in fibre ratio the shear stress increases and for 2%13mm the shear stress was 57.9MPa.

9.1.2(e) Study on Applications of RPC to Typical Structural Components

The enhanced mechanical properties of RPC led to the investigation of possibility of using RPC as structural components in Building frames. Various shapes of RPC structural sections viz., angle, I and channel were produced and investigated for their compression and flexural behavior. Since angle, sections are more often used for trusses and space frames, more extensive study was carried out on angle sections.

1 Compressive strength of 164MPa is obtained for angle sections with 2% 13mm fibre contents with high-energy absorption.

2 The failure in compression shows the failure is brittle, yet the high load carrying capacity of RPC angles makes it suitable for its usage as prefabricated structures.
3 The flexural stress varies from 7.62MPa to 28MPa which is very close to the values obtained for solid sections and also the high deflection.

4 Obtained (ranging from 5 mm to 11.3mm for 1%6mm to 2%13mm) confirms the possibility using RPC in prefabricated structures.

9.1.2(f) Study of RPC Infilled tubes

Investigations were also carried out bolted connections, as the use of structural sections in space frames requires proper design of joints. The studies showed the limitations of onsite fastening of RPC sections. To overcome this problem either prefabricated joints or infilled tubes can be cast using RPC and can be used as structural component. The connections will be easier in the case of steel tubes. So, infilled tubes with RPC with various fibre dosages were also investigated for compression.

The following were the conclusions derived from the testing of RPC infilled tubes:

1 Comparison of RPC infilled steel tube with normal MS hollow tube under compression reveals the strengthening effect of infilled RPC steel tubes.

2 The load capacities of infilled tubes were verified with predicted values using Eurocode, ACI and ASIC codal provisions. Of all the codal values the Eurocode.

3 All the experimental values were 20% higher than the codal values. Based on the results for RPC infilled tubes, the EC4 gives
us lower than that from experiments. Based on this it was suggested that EC04 can reliably predict the axial capacity of CFT columns using concrete strengths in the range 30-85MPa.

4 Also the values obtained from Mander’s model have a good correlation with the experimental results (8%-10%).

9.1.3 Direct Tension Test on RPC Bolted Plates

The possibility of usage of angle sections as structural components would not complete unless its connection details were optimized. So, the behavior of bolted RPC plates under direct tension is studied under different edge distances for various volumes of fibre content to optimize the bolted connections.

1 It is observed that there is an increase of 30 – 90% in first crack load with increase in edge distance.

2 Considering a simplified load dispersion at 45º, an edge distance of more than 2.5d may be necessary.

3 The ductility increases with the increase in length of the fibre showing the enhanced stitching action by the longer fibre between the materials of RPC.

4 The normalized strength ratio varies from 0.3 to about 0.6 for the range of parameters considered in the present study. It may be noted here that for a conventional steel plate connection, this ratio is taken as one. This indicates the reduced efficiency of bolted RPC plates compared to bolted steel plates under direct tension.
The results indicate that for bolted RPC members an edge distance of not less than $3.5d$ where $d$ is the diameter of bolt hole, with a minimum of $2\%$ of 13mm fibres will be suitable for structural assemblages.

**9.1.4 Analytical Models**

1. The angle sections both in compression and flexure were simulated using Ansys software. The results correlated well with the experimental results and the cracks simulated using the finite element analysis correlates well with the experimental crack pattern.

2. The load-deformation characteristics obtained from the finite element solution was in close agreement with the experimental results at four critical stages of loading.

3. The crack pattern at both initial and at failure predicted by FEM was in close agreement with the experiment results, indicating that the effect of fibres on the concrete strength and ductility and its bridging effects in arresting crack propagation have been suitably captured.

4. Although a very good correlation between the experimentally obtained and the modelled results for Reactive powder concrete is obtained, and it should be pointed out that a better understanding of the modelling parameters and the fracture processes in general is still necessary.
9.2 SCOPE FOR FUTURE WORK

Within this research project, a solid basis for the development and utilization of Reactive Powder Concrete has been made. Regarding the further development of material, the following points are recommended for future research.

1. **Further improvement of the properties of steel fibres:** The bond between the steel fibres and the concrete matrix can be improved by roughening the fibre surface. Moreover steel fibres of different shapes and geometries like fibres with enlarged ends, waved forms, twisted should be investigated for anchorage mechanisms and on the strength of bond and deformation.

2. **Optimization of Composition of RPC:** Production of Self-compacting Reactive Powder Concrete with homogeneously applied fibres accommodated between the aggregate grains. Other cement like filler materials can also be applied like blast furnace slag, rice husk ash, etc., and their influence on the workability and the bond between the fibres and concrete should be investigated.

3. **Application of polymer fibres:** Synthetic fibres (PVA, PVE) which are thinner and shorter than steel fibres can be added to RPC mix which will fill the spacing between the steel fibres and concrete. Nakamura et al., 2004, already published research results covering some of these topics.
The Shapes of the cross-sections of the structural elements made of RPC should further be optimized: This is especially important with regard to the more optimal utilization of the material in the tensile and compressive zone as well as with regard to the behaviour of structures in serviceability limit state such as deflections and vibrations. (some of the ideas were already discussed by Jungwirth and Muttoni, 2004\textsuperscript{4})

Behaviour of RPC in Structures During their Service life should be investigated: More research on durability fatigue of RPC is recommended. A full-scale model of truss can assembled and tested which will contribute tremendous improvements in the applications of RPC.