CHAPTER 7

CONCLUSIONS

7.1 INTRODUCTION

This study shows that RCA (Recycled Concrete Aggregate) in concrete can provide many technical benefits and it would also be fair to say provide many environmental and expected cost benefits. The study has shown that, regardless of original concrete type or strength, recycled good quality aggregates can be produced with plant similar to that used for the production of crushed – rock aggregates. Clearly, this information could encourage demolition contractors to direct demolished debris to the production of RCA for using new concrete, while reducing disposal to land fill.

For concrete producers, the use of RCA is unlikely to pose any problem in the production of concrete that is stable in the fresh state and able to develop properties comparable to corresponding natural aggregate concrete in the hardened state. The results of strength development demonstrate that the RCA source are original concrete type has a negligible effect on concrete strength, at a given RCA content. This is of importance to concrete producers who wish to supply RCA concrete and may draw recycled aggregate from different sources. The concrete durability results indicate that comparable performance irrespective of RCA content or source is achievable, providing the strengths of RCA concretes are matched.

Overall, the practical benefits resulting from this work are not only of an environmental nature, but also to provide the construction industry with technical information on a product which is at present underutilized.
The study reported in this thesis includes Mix design procedure for high performance concrete (HPC), Experimental investigations on strength characteristics of HPC and Experimental investigations on durability characteristics of HPC.

7.2 CONCLUSIONS

7.2.1 Mix Design Procedure for HPC

Concrete mix design procedure described here is more rational as it considers the effects of many properties of concrete ingredients, which are not taken into many conventional mix design methods. A simplified mix design procedure for HPC using mineral admixtures combined with a superplasticizer is formulated without violating BIS and ACI code regulations.

The proposed method of mix proportioning combined the use of superplasticizer and cement replacing materials for obtaining economical HPC mix. The trial mixes cast with the design mixes have given target strengths. Hence, the mix design procedure as suggested can be used for designing HPC using mineral admixtures like silica fume and fumed silica.

7.2.2 Experimental Investigations on Strength Characteristics of HPC

Based on the experimental investigations carried out on the strength characteristics of HPC mixes the following conclusions are arrived at:
### 7.2.2.1 Workability

- The workability of concrete as measured from slump and compaction factor decreases as percentage of silica fume and fumed silica in concrete increases, whereas for Vee-bee degree increases for all w/b ratios. This is not only due to the fact that as the percentage of silica fume and fumed silica increases the water available in the system decreases, thus affecting the workability, but also due to the presence of high pozzolanic reactive nature of silica fume and fumed silica with liberated calcium hydroxide.

### 7.2.2.2 Cube Compressive Strength

- At the age of 3, 7, 14, 28, 56 and 90 days, the compressive strength of HPC mixes containing silica fume and fumed silica was more than that of mixes without silica fume and fumed silica. This indicates that addition of silica fume and fumed silica as partial replacement to cement causes an increase in strength. Thus silica fume and fumed silica act as pozzolanic material. Hence the compressive strength of concrete increases as the percentage of those mineral admixtures increases.

- Cement replacement level of 15% with silica fume and 1% with fumed silica in concrete mixes was found to be the optimum level to obtain HPC at the age of 28 days at all w/b ratios. However, higher level of cement replacement is possible if strength at later ages such as 90 days could be considered for design.

- The 7-day and 14-day compressive strength of the HPC mixes was 60 to 78 and 85 to 92 percent of 28 days compressive strength respectively. This indicates that addition of silica fume and fumed silica as the partial replacement of cement causes early strength.
• There was an increase of only 5 to 7 MPa and 2 to 6 MPa in the compressive strength between 28 days and 90 days for concrete mixes without silica fume and fumed silica respectively, while this increase was in the range of 10 MPa to 16 MPa and 10 to 13 MPa for HPC mixes containing silica fume and fume silica. This could be advantageously used for design of structures such as bridge piers, abutment walls and other mass concrete structural elements where early strength is not a criterion.

• The compression failure pattern of concrete is due to crushing of coarse aggregate and not due to bond failure.

• The silica fume and fumed silica used in this investigation exhibits good pozzolanic properties. Therefore, it is strongly recommended for the production of HPC.

• The relationship between compressive strength and water-binder ratio of silica fume-based concrete with replacement of cement by silica fume is expressed as

\[
\sigma_{(c28)} = 25.982 (w/b)^{-0.8772} \quad \text{(for silica fume)} \quad (7.1)
\]

\[
\sigma_{(c28)} = 27.403 (w/b)^{-0.8125} \quad \text{(for fumed silica)} \quad (7.2)
\]

where

- \(f_c\) = Cube compressive strength of concrete at the age of 28 days in MPa
- \(w/b\) = Water-binder materials ratio

7.2.2.3 Cylinder Compressive Strength

• The optimum replacement of cement by silica fume and fumed silica for HPC mixes was found to be 15 and 1 percent respectively for achieving maximum cylinder compressive strength at the age of 28 days at all w/b ratios.

• The ratio between cylinder and cube compressive strength was found to be 0.89 at the age of 28 days.
7.2.2.4 Splitting Tensile Strength

- The optimum replacement of cement by silica fume and fumed silica for HPC was found to be 15 and 1 percent respectively for achieving maximum splitting tensile strength at the age of 28 days at all w/b ratios.
- The tensile strength increases along with increase in compressive strength. The tensile strength of HPC is 6 percent of cube compressive strength.
- The relationship between splitting tensile strength and cube compressive strength of silica fume and fumed silica -based concrete at 28 days is expressed as

\[
\begin{align*}
  f_t &= 0.0662 \, f_c^{0.9886} \quad \text{(for silica fume)} \\
  f_t &= 0.0229 \, f_c^{1.2279} \quad \text{(for fumed silica)}
\end{align*}
\]

where

- \( f_t \) = Splitting tensile strength of concrete at the age of 28 days in MPa, and
- \( f_c \) = Cube compressive strength of concrete at the age of 28 days in MPa.

7.2.2.5 Flexural Strength

- The optimum replacement of cement by silica fume and fumed silica for HPC was found to be 15 and 1 percent respectively for achieving maximum value of flexural strength at the age of 28 days at all w/b ratios.
- The flexural strength increases along with increase in compressive strength. The flexural strength of HPC is 9 to 10 percent of cube compressive strength.
The flexural strength of concrete at the age of 28 days was higher than the value calculated by the expression $0.7 \sqrt{f_{ck}}$ as specified in BIS:456-2000. The code BIS:456-2000 underestimates the value of flexural strength of silica fume and fumed silica-based HPC.

The relationship between flexural strength and cube compressive strength of silica fume and fumed silica-based concrete at 28 days is obtained as

$$f_r = 7.9490 \ f_c^{-0.1109} \quad (\text{for silica fume})$$

$$f_r = 2.3915 \ f_c^{-0.9162} \quad (\text{for fumed silica})$$

where

- $f_r =$ Modulus of rupture strength of concrete at the age of 28 days in MPa, and
- $f_c =$ Cube compressive strength of concrete at the age of 28 days in MPa

7.2.2.6 Modulus of Elasticity

The optimum replacement of cement by silica fume and fumed silica for HPC was found to be 15 and 1 percent respectively for achieving maximum value of modulus of elasticity at the age of 28 days at all w/b ratios.

The modulus of elasticity of concrete at the age of 28 days was more than the value calculated by the expression $5000 \sqrt{f_{ck}}$ as specified in BIS:456-2000. The value of modulus of elasticity obtained from silica fume and fumed silica based concrete are in accordance with code BIS:456-2000.

The relationship between modulus of elasticity and cube compressive strength of silica fume and fumed silica-based concrete at 28 days is obtained as

$$E_c = 23.530 \ f_c^{0.1155} \quad (\text{for silica fume})$$

$$E_c = 21.289 \ f_c^{0.1392} \quad (\text{for fumed silica})$$
where
\[ E_c = \text{Modulus of elasticity at the age of 28 days in GPa} \]
\[ f_c = \text{cube compressive strength of concrete at the age of 28 days in MPa}. \]

### 7.2.2.7 Flexural Toughness

- The toughness property of HPC mixes with silica fume and fumed silica was found to be more when compared to normal concrete mixes without silica fume and fumed silica at all w/b ratios.

### 7.2.2.8 Non Destructive Test

- In all cases of concrete mixes referred above, the ultrasonic pulse velocities at the age of 28 days were well above 4.5 km/sec which corresponds to excellent quality as per the guidelines given in BIS: 13311(Part 1)-1992. Hence, the non-destructive testing values are in good agreement with the strength behaviour of both silica fume, fumed silica based concrete and normal concrete for destructive testing.

### 7.2.3 Experimental Investigations on Durability Characteristics of HPC

Based on the experimental investigations carried out on the durability characteristics of HPC mixes, the following conclusions are arrived at:

#### 7.2.3.1 Saturated Water Absorption, Porosity and Sorptivity

- The saturated water absorption, porosity and sorptivity of HPC mixes containing silica fume and fumed silica were lower when compared with that of the concrete mixes without silica fume and fumed silica at all w/b ratios.
- Cement replacement level of 15 and 1 percent with silica fume and fumed silica in concrete mixes was found to be the optimum level to obtain lower value of the saturated water absorption, porosity and sorptivity at the age of 28 days and the same result was obtained at the age of 90 days also.

- The results of saturated water absorption, porosity and sorptivity tests have demonstrated superior durability characteristics of HPC mixes containing silica fume and fumed silica. This is due to the fact that micro structure in cement paste matrix is improved due to pozzolanic action and micro-pore filler effects of silica fume, resulting fine and discontinuous pore structure.

- Even a partial replacement of cement (which consumes high energy for its production) with silica fume and fumed silica in concrete mixes leads to considerable savings in consumption of cement and gainful utilization of mineral admixtures. Therefore, it can be concluded that replacement of cement with silica fume up to 15 percent and fumed silica up to 1 percent would render the concrete more durable and corrosion-resistant, besides meeting the strength requirements.

### 7.2.3.2 Permeability

- No percolation of water was found in all the concrete mixes at the age of 28 days and the same result was obtained at the age of 90 days also.

- The coefficient of permeability was found to be negligible in all the samples of concrete mixes containing silica fume and fumed silica, whereas the coefficient of permeability was more in concrete mixes
without silica fume and fumed silica. Hence, the addition of silica fume and fumed silica in concrete mixes makes the concrete denser and more impermeable.

- The presence of silica fume and fumed silica (which has very high fineness) in concrete mixes acts as micro-pore fillers and causes reduction in the pores, resulting fine and discontinuous pore structures and thereby increases the impermeability of concrete.

- Improved impermeability of the concrete results in increased resistance against the ingress of moisture and gases. The failure of moisture and gases to go through the densified concrete, results in the durability enhancement.

7.2.3.3 Acid Resistance

- The acid resistance of HPC mixes containing silica fume and fumed silica were higher when compared with that of the concrete mixes without those mineral admixtures at the age of 28 days at all w/b ratios.

- The acid resistance of concrete mixes was more when the percentage of replacement of silica fume and fumed silica in concrete mixes was also more up to the optimum replacement level. This indicates that the addition of silica fume and fumed silica in concrete mixes increases the acid resistance of HPC mixes.
7.2.3.4 Impact Strength

- The impact resistance of concrete mixes containing silica fume and fumed silica was higher when compared with that of the concrete mixes without silica fume and fumed silica at the age of 28 days.

- The impact resistance was more when the percentage of cement replacement by silica fume and fumed silica in concrete mixes was also more up to the optimum replacement level. This indicates that the addition of silica fume and fumed silica in concrete mixes increases the impact resistance.

7.2.3.5 Rapid Chloride Penetration

- The concrete mixes containing silica fume and fumed silica showed lower chloride ion penetrability when compared to normal concrete mixes.

- The concrete mixes containing 15 to 20 percentage of silica fume and 1 to 1.5 percentage of fumed silica replacement of cement, fall under the category of ‘Negligible’ degree of chloride ion penetrability as per ASTM C 1202 (1995). Thus, the higher the replacements of cement by silica fume and fumed silica, the higher the binding capacity and the lower the chloride ion penetrability or diffusivity. It proves that the use of mineral admixtures in concrete mixes as supplementary cementitious material enhances the durability and non-corrosion characteristics of concrete which is particularly effective in marine environments.
7.2.3.6 Accelerated Electrolytic Corrosion

- There is a significant reduction in loss of weight due to corrosion of reinforcement when silica fume and fumed silica is added in concrete mixes. Initiation of corrosion is also delayed when mineral admixtures are added to the concrete mixes.

- The concrete mixes containing 15 to 20 percent of silica fume and 1 to 1.5 percent of fumed silica replacement of cement have shown no corrosion and hence, addition of silica fume and fumed silica in concrete increases the corrosion resistance.

- The results of corrosion studies carried out on normal concrete mixes, silica fume and fumed silica-based concrete mixes reveal that the hardened matrix of concrete mixes containing silica fume and fumed silica is denser and more impermeable when compared to that of the concrete mixes without silica fume and fumed silica, and it can offer greater protection to corrosion of steel embedded in concrete.

- The corrosion of steel in mature concrete decreases as the content of silica fume and fumed silica proportion increases. This is evident from the corrosion studies carried out on normal concrete mixes and concrete mixes with silica fume and fumed silica.

7.2.3.7 Alkalinity Measurement

- The alkalinity of concrete mixes containing silica fume and fumed silica was a little less when compared with that of the concrete mixes without silica fume and fumed silica. This indicates that the addition of those mineral admixtures to concrete mixes reduces the pH of the pore solution to a limited extent only. Hence, the replacement of cement by
silica fume and fumed silica did not cause more loss of alkalinity and therefore, HPC mixes containing silica fume and fumed silica provide sufficient alkaline environment to the embedded steel and protect the steel from corrosion.

7.3 SUGGESTIONS FOR FUTURE WORK

The following are the suggestions for future work:

- The present investigation focused only a particular type of natural fine aggregate replacement material. Hence, investigations can be made on different types of artificial fine aggregates like crushed brick bats, foundry sand, colliery spoil, china clay waste and slate waste to study the mechanical and durability-related properties.

- This experimental work focused only a particular type of cement replacement materials. Hence, investigations can be made on different types of cement replacement materials (GGBS, rice husk ash, fly ash and metakaolin) to study the strength and durability-related properties.

- Studies could be conducted for other properties such as creep, shrinkage, carbonation resistance, microstructure, etc.

- Investigations may be carried out using RCA for prestressed concrete.