CHAPTER 5

CONCLUSIONS AND SUGGESTIONS

5.1 GENERAL

Based on the extensive experimental investigations carried out on the effect of steel slag aging on the strength and durability properties of high performance concrete, several vital conclusions are arrived. This chapter presents the summary of conclusions made based on the results of experimental investigations. The suggestions for future investigations are also indicated at the end.

From literatures, it is observed that steel slag is considered as potential alternative to natural aggregates and steel slag must be allowed to aging, before it is used as aggregates. There are different opinions about the aging period of steel slag. The research papers on the effect of aging period of steel slag on the properties of concrete are also quite rare. Hence, a detailed study is made to evaluate the effects of different aging periods of steel slag on the properties of concrete. Based on the strength and durability property test results, the feasibility of steel slag to use as concrete aggregate is evaluated and optimum aging period of steel slag is established. From the results of experimental investigations the following conclusions are arrived.
5.2 PROPERTIES OF STEEL SLAG AGGREGATE AND EFFECT OF AGING

- The physical and mechanical properties of the steel slag aggregate are found similar to those of natural coarse aggregate except free lime content (as shown in Table 3.3 and Figure 3.2). Hence, steel slag aggregate can be utilized as an alternative to natural coarse aggregate in concrete production after sufficient aging.

- Angularity of the steel slag aggregates is found to be decreased with increase in the aging period of SSA. However, the angularity of the steel slag aggregates (before and after aging) is higher than that of natural aggregate.

- The workability of HPC mixes containing SSA decreases with an increase in the aging period of SSA. Due to aging, free lime is removed from SSA by the weathering process. Hence, the lime pockets of the steel slag become empty, which leads to an increased surface area of aggregates, results in harsh mix with reduced workability. Dosage of superplasticizer can be increased to increase the workability. However, it is kept constant in this research to enable a more accurate comparison.

- The workability of all HPC mixes is higher than that of CC, because of addition of fly ash/silica fume and super plasticizer.

5.3 STRENGTH AND DURABILITY PROPERTIES OF HPC

- In the case of HPC mixes with fly ash, it is observed that the compressive strength of concrete is increased from 60.58 MPa to
78.50 MPa (from compressive strength results after 91 days curing) as the aging period of SSA is increased from 6 months to 42 months. Hence, it is concluded that a considerable improvement (29.6 %) in compressive strength of concrete is achieved, due to aging of SSA.

- In the case of HPC mixes with silica fume, it is observed that the compressive strength of concrete is increased from 61.60 MPa to 82.40 MPa (from compressive strength results after 91 days curing) as the aging period of SSA is increased from 6 months to 42 months. Hence, it is concluded that a considerable improvement (33.8 %) in compressive strength of concrete is achieved, due to aging of SSA.

- Optimum aging period of SSA is established as 30 to 36 months (if it is used along with fly ash). Optimum aging period of SSA is established as 24 to 30 months (if it is used along with silicafume). Thus, it might be sufficient to allow the steel slag aging up to that period because it is observed that beyond that period, an increase in strength results is quite minute.

- By considering compressive strength results of both the HPC mixes (HPC with fly ash/silica fume) it is concluded that increase in the aging period of SSA, results in increase of compressive strength of concrete irrespective of admixtures added.

- HPC with steel slag aggregates (after sufficient aging) and fly ash/silica fume shows better results than that of HPC with natural aggregates and fly ash/silica fume. Also it is observed that at earlier ages HPC mixes with fly ash gives less compressive strength than
that of HPC mixes with silica fume. But at later ages HPC mixes with fly ash show the compressive strength at par with the compressive strength of HPC mixes with silica fume. This is due to the delayed pozzalonic reaction of fly ash.

- The present results are found to be in good agreement with the previously reported results in case of both the HPC mixes with fly ash/silica fume (after sufficient aging of steel slag aggregate). Alizadeh et al. (2003); Maslehuddin et al. (2003); Papayianni & Anastasiou (2011); Nadeem & Pofale (2012) have reported that steel slag aggregate concretes achieved higher values of compressive strength, tensile strength, flexural strength and modulus of elasticity, compared to natural aggregate concrete.

- The flexural strength, Young’s modulus, impact strength and bond strength of concrete (in both the HPC mixes with fly ash/silica fume) increased with an increase in the aging period of steel slag aggregate, similar to the compressive strength.

- The relationship between the compressive strength and aging period of SSA is studied by the regression analysis. Equations showing the relationship are also derived. The relationship between compressive strength and aging period of SSA is found to be $Y=12.15x^{0.435}$ with $R^2 = 0.849$ for HPC with fly ash. The relationship between compressive strength and aging period of SSA is found to be $Y=31.36x^{0.233}$ with $R^2 = 0.989$ for HPC with silica fume. From the equations it is observed that the strength of concrete in compression and aging period of SSA are closely related.
The relationship between compressive strength and flexural strength of concrete is found to be \( Y = 0.761 \times 0.518 \) with \( R^2 = 0.912 \) for HPC with fly ash. The relationship between compressive strength and flexural strength of concrete is found to be \( Y = 0.849 \times 0.514 \) with \( R^2 = 0.997 \) for HPC with silica fume. These equations show good agreement with the findings of previous research works and the equation provided by the relevant Indian standard code.

Similarly the relationship between compressive strength and other strength properties of HPC mixes are studied by the regression analysis and it is found that compressive strength and other strength properties of HPC mixes are closely related.

The effect of steel slag aging period on efficiency factor of HPC mixes with fly ash/silica fume is analysed. It is observed that efficiency factor of concrete mixes increases as the aging period of SSA increases, for both the HPC mixes (with fly ash/silica fume). It is to be noted that efficiency factor of concrete mixes increases as the aging period of SSA increases, while all other parameters in the concrete mixes are constant. Hence, it is concluded that the aging process of SSA has a strong positive effect on the properties of concrete.

From the durability test results, it is found that the aging process of SSA has a strong positive effect on the durability properties of concrete, as in the case of strength properties.

Water absorption of concrete reduces as the aging period of SSA increases. The less water absorption characteristics of concrete can be attributed to the reduced free lime content in SSA due to aging,
superior quality of SSA and addition of chemical/mineral admixtures in the concrete. Therefore, incorporation of SSA (after sufficient aging) in concrete mixes reduces the water absorption of concrete significantly.

- In the case of HPC mixes with fly ash, the water absorption of HPCF is 21% less than that of CC. Water absorption of HPC4F, HPC5F, HPC6F and HPC7F is 2%, 16%, 22% and 29% less than that of CC.

- In the case of HPC mixes with silica fume, the water absorption test of HPCS is 24% less than that of CC. Water absorption of HPC4S, HPC5S, HPC6S and HPC7S is 12%, 22%, 32% and 35% less than that of CC.

- Based on water absorption test results of both the HPC mixes (HPC with fly ash/silica fume), it is concluded that increase in the aging period of SSA, results in the reduction of water absorption of concrete irrespective of admixtures added.

- Acid resistance and fire resistance of concrete (in both the HPC mixes with fly ash/silica fume) are increased with an increase in the aging period of steel slag aggregate.

- The porosity, abrasion loss and rapid chloride permeability of concrete (in both the HPC mixes with fly ash/silica fume) are reduced with an increase in the aging period of steel slag aggregate, similar to the water absorption.
The SEM analysis for both HPC7F and HPC7S (HPC with steel slag aggregate) specimens show a relatively dense and compact microstructure. Hence, the strength and durability properties of concrete with steel slag aggregate and fly ash/silica fume (HPC7F and HPC7S) are found superior when compared with control concrete.

### 5.4 Flexural Behaviour of HPC and Numerical Modeling Using ANSYS

- All HPC beams (HPCF, HPC7F, HPCS and HPC7S) show better performance than control beam (CC). An increase in ultimate load capacity and corresponding deflection in all the HPC beams is observed when compared with CC.

- The control beam shows a sudden failure after the yield load. The first crack load of CC beam is lesser than that of HPC beams. From the results a gain of about 30% in the first crack load, 24% in the yield load and 16% in the ultimate load for HPC7F beam is observed.

- Similarly a gain of about 50% in the first crack load, 36% in the yield load and 27% in the ultimate load for HPC7S beam is observed. The significant increase in the ultimate load may be due to the superior quality of SSA, better interlocking of SSA and cement paste and incorporation of fly ash/silica fume. Hence, more energy is required to propagate the crack path which results in increased load carrying capacity of beams.
• The ductility ratio increases by 1.49 times for HPCF beam, 1.87 times for HPCS beam, 2.57 times for HPC7F beam and 3.25 times for HPC7S beam, while comparing with the control beam. This significant increase in ductility shows that steel slag aggregates and mineral admixtures play an important role in the ductility behaviour of beams.

• It is observed that the stiffness of control beam is higher which shows a reduced ductility. When the steel slag aggregates and mineral admixtures are incorporated in the concrete, the stiffness of the HPC beams is reduced which results in the higher ductility of HPC beams.

• The difference in ultimate load obtained from experimental investigation and ANSYS analysis, ranges from 2.68% to 4.57%. The difference in ultimate deflection obtained from experimental investigation and ANSYS analysis ranges from 3.95% to 8.98%. It is concluded that there is no significant difference between experimental and analytical results.

5.5 ECONOMY OF HPC

• A saving in cement quantity of 25% is achieved in HPC mixes with fly ash (mixes HPCF and HPC7F) while comparing with CC.

• A saving in cement quantity of 10% is achieved in HPC mixes silicafume (mixes HPCS and HPC7S) while comparing with CC.

• HPC7F is found to be most economical than other mixes which gives a reduction of 11% in the total cost of concrete along with
25% saving in cement and 100% saving in natural coarse aggregate (HBG).

- A saving in natural coarse aggregates of 100% is achieved in the mixes HPC7F and HPC7S. In these mixes natural coarse aggregates are completely replaced by steel slag aggregates. In these mixes a saving of 73% of coarse aggregate cost is reduced when comparing with control concrete.

5.6 GENERAL CONCLUSIONS

- The aging process of steel slag aggregates has a strong positive effect on the properties of concrete. It is concluded that an increase in the aging period of steel slag aggregates, improves the strength and durability properties of concrete irrespective of admixtures added.

- If the steel slag aggregates are used in concrete prior to aging, the free lime particles in the lime pockets of the steel slag aggregates may react with water and expand individually, producing uneven stress, and resulting in poor quality of concrete. When the steel slag aggregates are subjected to aging at stockpiles, the risk of free lime expansion is minimized because of the prior hydration of free lime content, due to continuous weathering in open air, contact with rain water, humidity, etc. After a long aging period, the free lime is completely removed by the weathering process. Hence the lime pockets of the steel slag become empty, which leads to an enhanced interlocking between aggregates and the cement paste. Therefore, the quality of concrete will be better if the steel slag aggregates are used after aging.
The optimum aging period of steel slag is obtained as 30 to 36 months, if it is used along with fly ash. The optimum aging period of steel slag is obtained as 24 to 30 months, if it is used along with silica fume. HPC mixes with silica fume show better performance than HPC mixes with fly ash.

HPC beams made with steel slag aggregates show a better performance than the beams made with natural aggregates. The load carrying capacity and deflection values obtained from experimental investigation are compared with analytical (ANSYS) results and found to be satisfactory.

HPC mixes with fly ash are found to be more economical than all other mixes.

In general, the HPC prepared with steel slag aggregates and admixtures have performed much better than the concrete cast with conventional aggregates. Hence the use of steel slag aggregates (after sufficient aging) in concrete is recommended.

It is concluded that, the steel slag (after sufficient aging) can be used as concrete aggregate along with chemical and mineral admixtures, to produce a higher quality concrete.

The use of steel slag aggregates as a substitute for natural aggregates offers technical, economic and environmental advantages, which are of great importance in the present context of sustainability in the construction sector.
5.7 SUGGESTIONS FOR FUTURE WORK

The following suggestions are made for the future works in this current area of research.

- Investigations may be carried out in the concrete mixes, with constant slump, by suitably modifying the proportions of super plasticizers /mineral admixtures. In the present study proportions of super plasticizers /mineral admixtures are kept as constant.

- Investigations may be carried out in the concrete mixes, by finding the optimum proportion of fly ash/silica fume separately with natural aggregates and steel slag aggregates to reduce the cement content further. In the present study the optimum proportion of fly ash/silica fume obtained in the case of natural aggregate is used for the steel slag aggregates also.

- Investigation may be carried out to study the behaviour of other structural elements like columns and slabs. In addition behaviour of RC frames may also be studied. More detailed studies can be made in the flexural behaviour of beams.

- Performance of concrete using steel slag aggregates along with other mineral admixtures such as Ground Granulated Blast Furnace Slag, Rice Husk Ash, Metakaolin, Sugarcane Bagasse Ash, etc., may be investigated.

- Suitability of steel slag as fine aggregate in concrete may be investigated. Effect of using steel slag as coarse aggregate and fine aggregate in concrete may be investigated.
• Effect of other aging methods such as hot water aging and steam aging may be investigated. These methods of aging can be used to reduce the optimum aging period (when compared to air aging) of steel slag aggregates.

• Investigation may be carried out to study the effect of “change in the physical and mechanical properties of steel slag aggregates” due to aging may be investigated.

• The stress block parameters and the Moment curvature relations can be investigated in detail. Microstructure of concrete with steel slag aggregates may be investigated in detail.

• Investigations may be carried out to study the performance of concrete beyond 91 days.

• Investigations may be carried out to study the hydration process and Alkali Silica Reaction.

5.8 PRACTICAL SIGNIFICANCE OF THE WORK

The idea of this work is to research on alternate aggregate resources like steel slag aggregate as a total replacement for natural aggregate. The use of steel slag aggregate in concrete production will address the problems related to scarcity of natural aggregate and also provides solution to the disposal problem of waste steel slag.

“Aging” is must and an important criterion in the utilization of steel slag aggregates. In this work “optimum aging period” is taken as the research problem. Aging in the form of open air stacking (air aging) is
adopted, since this method is easier and cost effective. Based on the test results of this research, the optimum air aging period (i.e., to obtain maximum possible benefits of air aging) is established as 24-30 months. However, steel slag aggregate can be used well before this aging period depending on the properties of concrete required. “Steel slag aggregate processing units” can be established in steel industries for effective utilization of waste steel slag.

There are many other methods of steel slag aging such as, steam aging, hot water aging, etc. These methods of aging can be used to reduce the optimum aging period (when compared to air aging) of steel slag aggregate. However, the possibility of substituting natural aggregate with industrial by-product aggregate (like steel slag aggregate) offers technical, economic and environmental advantages, which are of great importance in the present context of sustainability in the construction sector.
APPENDIX 1

A.1  FLEXURAL STRENGTH EQUATION

The flexural strength or modulus of rupture is established from simple bending equation as explained blow.

Simple bending equation; \[ M/I = F_{cr}/Y. \]

Where,  \( M \) = bending moment at failure; \( I \) = Moment of inertia of the section; \( Y \) = distance of extreme fibre from neutral axis, \( F_{cr} \) = Flexural Strength or modulus of rupture.

Also, \[ F_{cr} = (M/I) \times Y \]

In the flexural strength test of concrete (two point loading); Cross section\( =B \times D \); Span of the beam\( =L \); Load at failure (total load)\( =P \); Load value in each point of two point loading \( =P/2 \).

Therefore, \[ M = P/2 \times L/3; \quad I = BD^3/12; \quad Y = D/2 \]

By substituting the above values in simple bending equation,

\[ F_{cr} = \left\{ P/2 \times L/3 \right\} \times \left\{ D/2 \right\} / \left\{ BD^3/12 \right\} \]
On simplifying, the flexural strength is established as,

\[ f_{cr} = \frac{PL}{BD^2} \]  \hspace{1cm} (3.1)

Where, \( f_{cr} \) = Flexural strength of the specimen in MPa

\( P \) = load in Newton applied to the specimen

\( L \) = Span in mm, \( B \) = Width of the specimen in mm

\( D \) = Depth of the specimen in mm