CHAPTER 8

Conclusions and Scope of Further Study

8.1 Introduction

The concept of carbonation of concrete and its experimental analysis has been well established by many researchers. However, some discrepancies have been observed in the previous research findings, with respect of the impact of external and internal factors on the carbonation of concrete. Also, the findings on the carbonation resistance of blended cement concretes with mineral admixtures calls for more finer understanding. Further, the need for simultaneous analysis of the factors affecting the compressive strength of concrete was also considered to be important in assessing the durability and strength parameters of concrete. Thus, the present research attempts to analyze the experimental results of the above factors on carbonation, as well as that on compressive strength. Also, experimental results have been analyzed by both conventional and advanced methods to draw a comparison of the test methodologies.

This chapter details the conclusions made from the present research, the suggestions in dealing with carbonation resistance of concrete and the recommendations for the future studies. Conclusions drawn from the experimental investigations are stated below.

8.2 Impact of W/C Ratio

Carbonation depth increases with increase in W/C ratio from 0.4 to 0.5 for both OPC and PPC concrete .The increase in water content of concrete results in more homogenous mix which is more porous and thus facilitates ingress of $CO_2$and movement of particles, resulting in increased carbonation depth.

8.3 Impact of Type of Cement

Carbonation depths in PPC concrete are higher than those observed in the corresponding OPC concrete. PPC is produced by Fly ash replacement of clinker in OPC. The CH content of PPC is thus lower. Thus, as compared to OPC, CO_2reacts with lower CH content in PPC and ingresses deeper more easily. It may be mentioned that since fly ash particles are finer than clinker, PPC concrete has less voids and thus carbonation resistance of PPC concrete increases. Still, the impact of reduced CH content supersedes and the resultant carbonation depth is found to increase in case of PPC.

8.4 Impact of CO_2 Concentration

Increase in curing period results in lower carbonation depths for both OPC and PPC concrete. Higher concentration of CO_2 implies more speedy reaction with CH resulting in greater depths of carbonation.

8.5 Impact of Relative Humidity

Carbonation increases with the increase in relative humidity upto85 % and then decreases upon further increase of RH up to 100 % for both OPC and PPC concrete. The increase in RH increases the moisture content thus increasing the solubility of CO_2 within the pores, hence facilitating movement of CO_2 within the pores. However, after about 85 % RH, the pores are fully saturated with moisture. The pores are thus blocked which resists the transportation of CO_2 through the pores.

8.6 Impact of Curing Period

Carbonation decreases with the increase in curing period for both OPC and PPC concrete. Longer curing period increases hydration of cement and decreases its porosity. The permeability of concrete is thus reduced resulting in lower depths of carbonation.

8.7 Impact of Period of Exposure

Carbonation increases with the period of exposure for both OPC and PPC concrete. Carbonation increases with the period of exposure for both OPC and PPC concrete. This indicates that the impact of carbonation progressively increases with time.

8.8 Impact of External Protective Covers like Plaster and Paint

The depth of carbonation is found to be lower in concrete with 12 mm plaster and further lower with concrete having plaster and acrylic emulsion paint protection. External covers like paint and plaster offer resistance to entry of deleterious materials and thus reduces the vulnerability of concrete to deterioration from carbonation.

8.9 Impact of the Addition of Super Plasticizer

The use of super plasticizer reduces the effect of carbonation on both OPC and PPC concrete. Super plasticizers increase the workability of cement. It makes the concrete mix more homogenous and increases its resistance to permeability and subsequently carbonation. The addition of super plasticizer does not have any impact on compressive strength; however, it drastically reduces cement consumption in concrete. Thus the addition of super plasticizer is recommended for both carbonation resistance and reduction of cement consumption.

8.10 Impact of the Addition of FA as Cement Replacement

Carbonation reduces on replacement of cement with fly ash initially up to 10 % replacement and subsequently increases with increase of percentage replacement from 10 to 70 % for both OPC and PPC concrete. Fly ash consists of very fine particles which can help to fill the voids in concrete mix and reduce pores, thus reducing its permeability, in turn decreasing the effect of carbonation. However, this advantage of Fly ash replacement of cement is observed only up to 10 %. Beyond this percentage, fly ash replacement causes major decrease in the CH content of concrete mix which reduces the basic environment of the concrete mix. Thus, the resultant increase in carbonation supersedes the former effect.

A consistent decrease in compressive strength is found upon addition of fly ash as cement replacement. Thus, fly ash replacement of cement is recommended only up to 10 % if strength requirement of the structure permits.

8.11 Impact of the Addition of Micro Silica as Cement Replacement

Carbonation reduces on replacement of cement with micro silica initially up to 10 % replacement and subsequently increases with increase of percentage replacement from 10 to 70 % for both OPC and PPC concrete. Micro silica consists of fine particles that fill up the pores to reduce the permeability of concrete mix, which in turn reduces the carbonation. However, upon higher replacement beyond 10 % the SiO_2content of micro silica reacts with CH and the clinkers are diluted to reduce the CH content of the mix which increases the carbonation depths.

The addition of micro-silica as cement replacement to concrete has also shown an increase in compressive strength up to 10% replacement and then significant decrease beyond 10 % replacement. Thus both strength and carbonation resistance increase up to 10% replacement of cement with micro silica. Accordingly, a replacement of 10 % by mass of cement with micro silica is recommended for enhancing durability and strength of concrete.

8.12 Impact of the Addition of GGBS as Cement Replacement

Carbonation reduces on replacement of cement with GGBS initially up to 30 % replacement and subsequently increases with increase of percentage replacement from 10 to 70 % for both OPC and PPC concrete. GGBS consists of fine particles. At lower percentages of replacement of cement with GGBS voids in concrete are considerably filled and permeability decreases thus reducing carbonation, whereas higher replacement results in enhanced reduction of $Ca(OH)_2$ content of cement which reduces the basic environment of concrete mix and facilitates higher carbonation.

The addition of blast furnace slag as cement replacement to concrete has also shown an increase in compressive strength up to 30 % and then significant decrease.

Thus cement replacement of GGBS can be recommended up to 30 % by mass of OPC for enhancing both durability and strength of concrete.

8.13 Impact of the Addition of FA as Fine Aggregate Replacement

The replacement of fine aggregate with fly ash results in a decrease in carbonation for both OPC and PPC concrete. This may be attributed to the finer particle size of fly ash with respect to Fine aggregate and no dilution of clinker, thus resulting in no reduction of CH content. Thus, fine aggregate may be replaced with FA for reduction of carbonation, subject to meeting other performance parameters in concrete.

8.14 Impact of the Addition of GGBS as Fine Aggregate Replacement

The replacement of fine aggregate with GGBS results in a decrease in carbonation for both OPC and PPC concrete. This may be attributed to the finer particle size of GGBS with respect to Fine aggregate and no dilution of clinker, thus resulting in no reduction of CH content.

The replacement of OPC with Fly Ash, micro silica and GGBS gives nearly comparable results, however least values of carbonation depths have been noted for replacement with GGBS.

8.15 Accuracy of Experimental Procedures

The results of carbonation depth obtained from phenolphthalein indicator are nearly half the values obtained from advanced techniques. The results of advanced methodologies i.e. XRD, FTIR and SEM are all comparable.

8.16 Compressive Strength

Compressive strength of carbonated concrete is greater than that of non-carbonated concrete. Carbonation involves reaction of CO_2 with the CH content to form $CaCO_3$ which results in increased strength of the concrete mix.

8.17 Inference

In view of the experimental results, it may not be out of place to mention that, since in the natural environment the rate of carbonation is extremely slow, and it is difficult to measure the carbonation in an actual structure, with effective life being much longer than the scope of an experiment, it is only possible to determine the estimated effect of carbonation, based on accelerated experiments. Also, since the experiments are conducted in accelerated chamber under controlled conditions, results are only indicative and can only be analyzed to understand the gross nature of impact of various factors and the trend of their influence approximately. As such the following can be broadly inferred:

a. Use of OPC is recommended against PPC to reduce the risk of carbonation.

b. The use of super plasticizers reduces the effect of carbonation in both OPC and PPC concrete and also reduces cement consumption.

c. In areas of high CO_2 concentration, protective covers such as acrylic emulsion paints over plaster is recommended for reduced effect of carbonation.

d. Replacement of fine aggregate with fly ash/GGBS is recommended for both OPC and PPC concrete to reduce the effect of carbonation subject to complying with the strength requirement.

e. Replacement of OPC cement with fly ash or micro silica up to 10%.is recommended for reducing carbonation of concrete.

f. Replacement of OPC cement with up to 30% of GGBS is recommended for reducing carbonation in concrete.

g. Use of OPC + 0-30 % GGBS replacement of cement + 0-10 % Fly ash replacement of cement is recommended.

h. Use of OPC + 0-25% GGBS replacement of cement + 0-5% Micro silica is recommended

i. Use of PPC Cement blended with 2.5% GGBS or 2.5 % micro silica is recommended.

j. Longer curing period is recommended for both OPC and PPC concrete to reduce the risk of carbonation.

8.18 Scope of Further Study

In the above research, factors influencing carbonation has been tested with phenolphthalein indicator method while only some cases have been examined by advanced methods. Also, only compressive strength, being one of the major performance characteristics of concrete has been examined for few samples to simultaneously review the impact of factors on strength and carbonation resistance. Recommendations made above are only in view of the experimental scope of this study consisting of carbonation resistance and compressive strength. However, there are other performance characteristics of concrete, which may be affected by the combinations recommended above and may not be suitable for structures under specific circumstances. Thus, there is scope for further study in this area and can be proposed as follows:

1. Analysis of carbonation depths by further test methods, such as TGA, etc. to determine the accuracy of results.
2. The present experiment deals only with three types of mineral admixture, i.e. fly ash, micro silica and blast furnace slag as partial cement replacement materials. Other mineral admixtures, such as marble dust and rice husk can be used to check their impact on carbonation resistance as a partial cement replacement.
3. Test may also be conducted effectively on Portland slag cement.