Chapter 4

The Test Results and Discussions

4.1 Introduction

Different factors such as curing period, addition of super plasticizer, replacement of cement with Fly Ash, micro silica, GGBS, amongst others have been varied in test cube samples and the samples have been tested by the conventional phenolphthalein indicator method. Concrete samples with variable mix proportions as per experimental programme have been tested for carbonation depth by phenolphthalein indicator method at fixed parameters i.e. 3 days curing period, 4 % CO_2 concentration and 65 % relative humidity and retention period of 20 days in carbonation chamber at three different W/C ratios. Further, some samples have been tested by phenolphthalein indicator method upon variation of parameters like CO_2 concentration, curing period and RH percentage. However, some cases have also been tested by advanced methods for comparison of results.

Since the above variations also bear impact on the compressive strength of concrete which is the major characteristic of concrete in construction, compressive strength of specific samples under such variation have also been tested. An ideal set of parameters can be adjudged where the result of carbonation depth decreases without considerably affecting the compressive strength of concrete.

The following texts elaborate the experimental results obtained through various methods under various parameters.

4.2 Carbonation Depth from Phenolphthalein Indicator

4 % CO_2, 65 % RH and period of exposure 20 days

4.2.1 OPC Concrete (Without Super Plasticizer)

The results of the carbonation of the reference OPC concrete mixes, with W/C ratio varying over a range of 0.4 to 0.5 and cured for a period of 3, 7, 21, 28 and 56 days, before exposing them to a rapid carbonation environment in the laboratory, as stated above, are given in table 4.1 and shown plotted in Figure 4.1

Table 4.1 Carbonation Depth of OPC Concrete Mixes (Without Super Plasticizer)

Mix	W/C	Carbonation Depth (mm)				
		Period of Curing (Days)				
		3	7	21	28	56
O_1	0.4	4.4	4.1	4	3.9	3.7
O_2	0.45	7.5	6.9	6.7	6.5	6.3
O_3	0.5	10.1	9.1	8.8	8.5	8.3

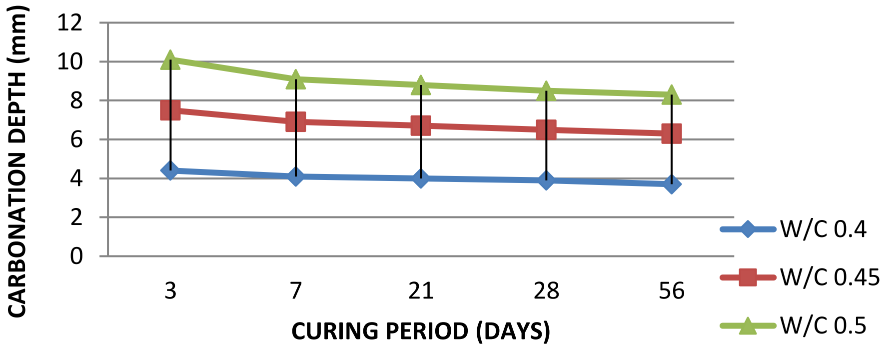


FIG.4.1 - Carbonation Depth of OPC Concrete at without Super Plasticiser

It is evident from test results that carbonation depth increases with increase in water cement ratio. This can be attributed to the increase in porosity of concrete with the increase of W/C, which subsequently facilitates the ingress of deleterious materials through the structure.

It may further be observed from the results that for OPC concrete, Carbonation depth decreases as the curing period increases. Longer curing period increases hydration of cement and decreases porosity, which in turn reduces the permeability of concrete and thus decreases penetration through carbonation.

4.2.2 OPC Concrete (With Super Plasticizer)

The results of the carbonation of the reference OPC concrete mixes, with W/C ratio varying over a range of 0.4 to 0.5 and cured for a period of 3, 7, 21, 28 and 56 days, before exposing them to a rapid carbonation environment in the laboratory, as stated above, are given in table 4.2 and shown plotted in Figure 4.2

Table 4.2 Carbonation Depth of OPC Concrete Mixes (With Super Plasticizer)

Mix	W/C	Carbonation Depth (mm)				
		Period of Curing (Days)				
		3	7	21	28	56
OS_1	0.4	3.8	3.6	3.5	3.4	3.2
OS_2	0.45	6.3	6.1	5.7	5.6	5.5
OS_3	0.5	8.7	8.2	7.7	7.4	7.2

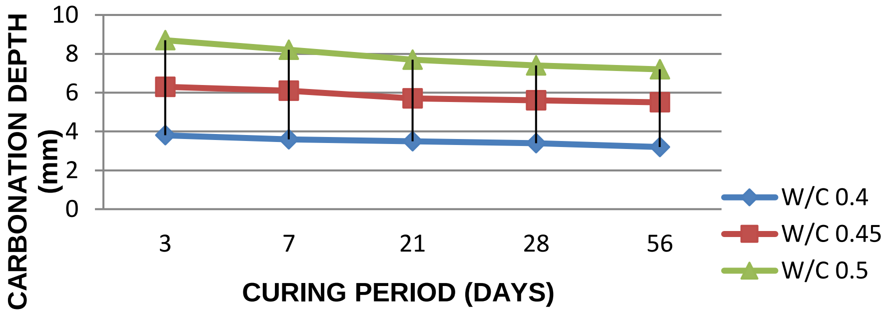


FIG.4.2 - Carbonation Depth of OPC Concrete using Super Plasticizers

While it is established from the above results that carbonation depth increases with increase in water cement ratio and that carbonation depth decreases with increasing curing period, it can also be seen from the above experimental data that use of super plasticizer reduces the effect of carbonation in concrete. Superplasticizers are applied to increase the workability of cement which thus increases its resistance to permeability and subsequently carbonation.

4.2.3 OPC Concrete with Fly Ash Replacement of Cement

The results of the carbonation of the reference OPC concrete mixes, with W/C ratio varying over a range of 0.4 to 0.5, with 10, 30, 50 and 70% replacement of cement with fly ash and cured for a period of 3 days, before exposing them to a rapid carbonation environment in the laboratory, as stated above, are given in table 4.3 and shown plotted in Figure 4.3

Table 4.3 Carbonation Depth of OPC Concrete Mixes with Fly Ash Replacement of Cement

W/C	Percentage Replacement	Mix	Carbonation Depth (mm)
0.4	No replacement of cement	O_1	4.4
	10 % replacement of cement with Fly Ash	OF_3	3.9
	30 % replacement of cement with Fly Ash	OF_6	4.4
	50 % replacement of cement with Fly Ash	OF_9	4.5
	70 % replacement of cement with Fly Ash	OF_{12}	4.6
0.45	No replacement of cement	O_2	7.5
	10 % replacement of cement with Fly Ash	OF_2	7.1
	30 % replacement of cement with Fly Ash	OF_5	7.9
	50 % replacement of cement with Fly Ash	OF_8	8.2
	70 % replacement of cement with Fly Ash	OF_{11}	8.4
0.5	No replacement of cement	O_3	10.1
	10 % replacement of cement with Fly Ash	OF_1	9.7
	30 % replacement of cement with Fly Ash	OF_4	11.1
	50 % replacement of cement with Fly Ash	OF_7	12
	70 % replacement of cement with Fly Ash	OF_{10}	12.5

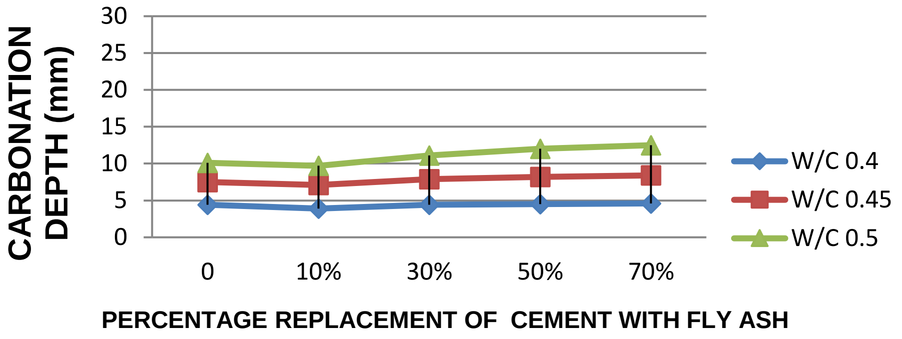


FIG.4.3 - Carbonation Depth of OPC Concrete with Fly Ash Replacemet of Cement

It can be observed from test results that for OPC concrete, depth of carbonation initially reduces up to 10 % replacement of cement with FA. However, increase in percentage replacement of cement with FA results in an increase of carbonation. This indicates that while lower percentages of replacement of cement with FA can considerably help filling the voids in concrete and reduce permeability thus reducing carbonation, 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.

4.2.4 OPC Concrete with Micro Silica Replacement of Cement

The results of the carbonation of the reference OPC concrete mixes, with W/C ratio varying over a range of 0.4 to 0.5, with10, 30, 50 and 70% replacement of cement with Micro silica and cured for a period of 3 days, before exposing them to a rapid carbonation environment in the laboratory, as stated above, are given in table 4.4 and shown plotted in Figure 4.4

Table 4.4 Carbonation Depth of OPC Concrete Mixes with Micro Silica Replacement of Cement

W/C	Percentage Replacement	Mix	Carbonation Depth (mm)
0.4	No replacement of cement	O_1	4.4
	10 % replacement of cement with Micro silica	OM_3	3.9
	30 % replacement of cement with Micro silica	OM_6	5.5
	50 % replacement of cement with Micro silica	OM_9	5.8
	70 % replacement of cement with Micro silica	OM_{12}	5.9
0.45	No replacement of cement	O_2	7.5
	10 % replacement of cement with Micro silica	OM_2	6.8
	30 % replacement of cement with Micro silica	OM_5	9.4
	50 % replacement of cement with Micro silica	OM_8	10.1
	70 % replacement of cement with Micro silica	OM_{11}	10.5
0.5	No replacement of cement	O_3	10.1
	10 % replacement of cement with Micro silica	OM_1	9.4
	30 % replacement of cement with Micro silica	OM_4	12.6
	50 % replacement of cement with Micro silica	OM_7	13.2
	70 % replacement of cement with Micro silica	OM_{10}	14.5

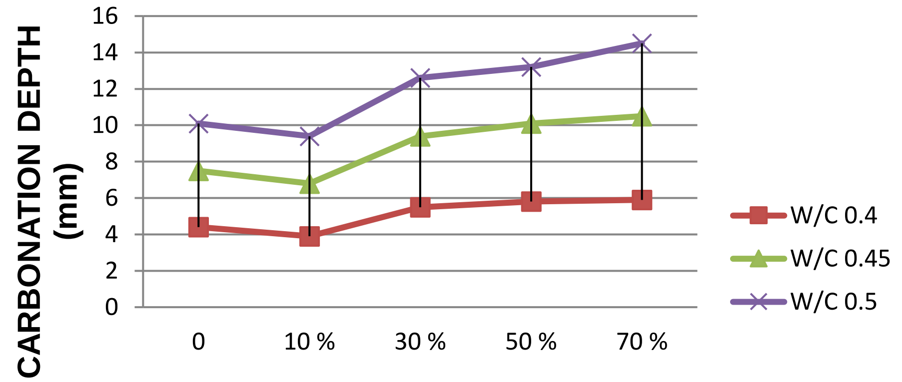


FIG.4.4 - Carbonation Depth of OPC Concrete with Microsilica Replacement of Cement

It can be observed from test results that for OPC concrete, depth of carbonation initially reduces up to 10 % replacement of cement with micro silica. However, increase in percentage replacement of cement with micro silica results in an increase of carbonation. This indicates that while lower percentages of replacement of cement with FA can considerably help filling the voids in concrete and reduce permeability thus reducing carbonation, 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.

4.2.5 OPC Concrete with Fly Ash Replacement of Fine Aggregate

The results of the carbonation of the reference OPC concrete mixes, with W/C ratio varying over a range of 0.4 to 0.5, with10, 30, 50 and 70% replacement of fine aggregate with fly ash and cured for a period of 3 days, before exposing them to a rapid carbonation environment in the laboratory, as stated above, are given in table 4.5 and shown plotted in Figure 4.5

Table 4.5 Carbonation depth of OPC Concrete Mixes with Fly Ash Replacement of Fine Aggregate

W/C	**Percentage Replacement**	**Mix**	**Carbonation Depth (mm)**
0.4	No replacement of Fine aggregate	O_1	4.4
	10 % replacement of Fine aggregate with Fly Ash	OFF_3	3.9
	30 % replacement of Fine aggregate with Fly Ash	OFF_6	3.4
	50 % replacement of Fine aggregate with Fly Ash	OFF_9	3
	70 % replacement of Fine aggregate with Fly Ash	OFF_{12}	2.8
0.45	No replacement of Fine aggregate	O_2	7.5
	10 % replacement of Fine aggregate with Fly Ash	OFF_2	6.6
	30 % replacement of Fine aggregate with Fly Ash	OFF_5	5.9
	50 % replacement of Fine aggregate with Fly Ash	OFF_8	5.3
	70 % replacement of Fine aggregate with Fly Ash	OFF_{11}	4.7
0.5	No replacement of Fine aggregate	O_3	10.1
	10 % replacement of Fine aggregate with Fly Ash	OFF_1	9.5
	30 % replacement of Fine aggregate with Fly Ash	OFF_4	8.5
	50 % replacement of Fine aggregate with Fly Ash	OFF_7	8.2
	70 % replacement of Fine aggregate with Fly Ash	OFF_{10}	8

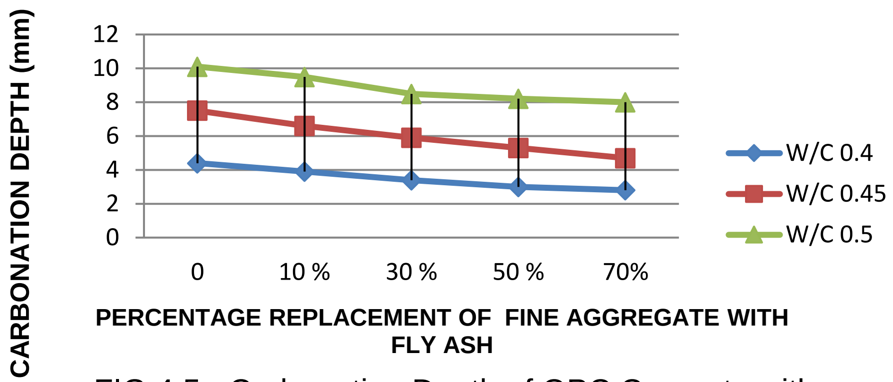


FIG.4.5 - Carbonation Depth of OPC Concrete with Fly Ash Replacement of Fine Aggregate

It can be observed from the above test results that for OPC concrete, depths of carbonation decreases with increase in percentage replacement of fine aggregate with FA. It may be noted that results of cement replacement and fine aggregate replacement with FA do not follow the same pattern. Since fine aggregate does not contribute to cementitious properties and FA replacement of fine aggregate further reduces porosity, increased replacement consistently increases carbonation resistance in case of the latter.

4.2.6 OPC Concrete with GGBS Replacement of Cement

The results of the carbonation of the reference OPC concrete mixes, with W/C ratio varying over a range of 0.4 to 0.5, with10, 30, 50 and 70% replacement of cement with GGBS and cured for a period of 3 days, before exposing them to a rapid carbonation environment in the laboratory, as stated above, are given in table 4.6 and shown plotted in Figure 4.6

Table 4.6 Carbonation Depth of OPC Concrete Mixes with GGBS Replacement of Cement

W/C	Percentage Replacement	Mix	Carbonation Depth (mm)
0.4	No replacement of cement	O_1	4.4
	10 % replacement of cement with GGBS	OG_3	3.7
	30 % replacement of cement with GGBS	OG_6	3.5
	50 % replacement of cement with GGBS	OG_9	4.3
	70 % replacement of cement with GGBS	OG_{12}	4.5
0.45	No replacement of cement	O_2	7.5
	10 % replacement of cement with GGBS	OG_2	6.9
	30 % replacement of cement with GGBS	OG_5	6.7
	50 % replacement of cement with GGBS	OG_8	8
	70 % replacement of cement with GGBS	OG_{11}	8.4
0.5	No replacement of cement	O_3	10.1
	10 % replacement of cement with GGBS	OG_1	9.5
	30 % replacement of cement with GGBS	OG_4	9.2
	50 % replacement of cement with GGBS	OG_7	11.5
	70 % replacement of cement with GGBS	OG_{10}	12

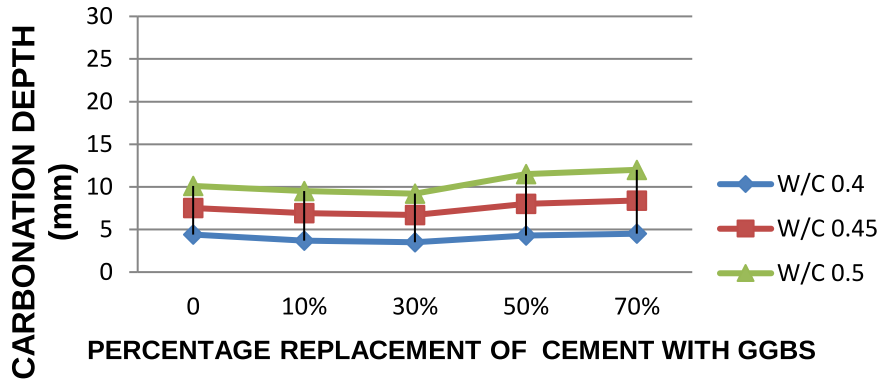


FIG.4.6 - Carbonation depth of OPC Concrete with GGBS Replacement of Cement

It can be observed from the above test results that for OPC concrete, carbonation depth initially decreases up to 30 % replacement of cement with GGBS and subsequently increases on increasing percentage replacement. This indicates that while lower percentages of replacement of cement with GGBS can considerably help filling the voids in concrete and reduce permeability thus reducing carbonation, 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.

It may further be noted that decrease in carbonation in case of cement replacement with GGBS is observed up to 30 % while that in case of FA replacement is up to 10 % only. This may be accounted for by the comparatively higher binding property of GGBS over FA on account of the $Ca(OH)_2$ content of the former.

4.2.7 OPC Concrete with GGBS Replacement of Fine Aggregate

The results of the carbonation of the reference OPC concrete mixes, with W/C ratio varying over a range of 0.4 to 0.5, with 10, 30, 50 and 70% replacement of fine aggregate with GGBS and cured for a period of 3 days, before exposing them to a rapid carbonation environment in the laboratory, as stated above, are given in table 4.7 and shown plotted in Figure 4.7

Table 4.7 Carbonation Depth of OPC Concrete Mixes with GGBS Replacement of Fine Aggregate

W/C	Percentage Replacement	Mix	Carbonation Depth (mm)
0.4	No replacement of Fine aggregate	O_1	4.4
	10 % replacement of Fine aggregate with GGBS	OFG_3	3.8
	30 % replacement of Fine aggregate with GGBS	OFG_6	3.2
	50 % replacement of Fine aggregate with GGBS	OFG_9	2.9
	70 % replacement of Fine aggregate with GGBS	OFG_{12}	2.7
0.45	No replacement of Fine aggregate	O_2	7.5
	10 % replacement of Fine aggregate with GGBS	OFG_2	6.5
	30 % replacement of Fine aggregate with GGBS	OFG_5	5.9
	50 % replacement of Fine aggregate with GGBS	OFG_8	5.2
	70 % replacement of Fine aggregate with GGBS	OFG_{11}	4.8
0.5	No replacement of Fine aggregate	O_3	10.1
	10 % replacement of Fine aggregate with GGBS	OF_{G1}	9.4
	30 % replacement of Fine aggregate with GGBS	OFG_4	8.5

50 % replacement of Fine aggregate with GGBS	OFG_7	8.1
70 % replacement of Fine aggregate with GGBS	OFG_{10}	7.9

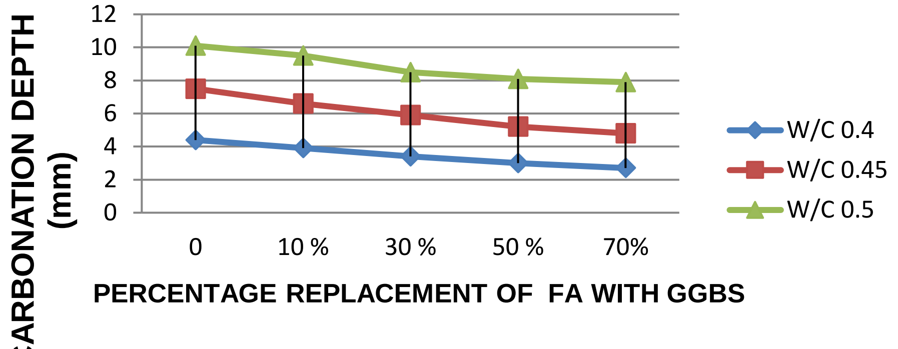


FIG.4.7 - Carbonation Depth of OPC Concrete with GGBS Replacement of Fine Aggregate

It can be observed that for OPC concrete, carbonation reduces with increase in percentage replacement of fine aggregate with GGBS. It may be noted that results of cement replacement and fine aggregate replacement with GGBS do not follow the same pattern. Since fine aggregate does not contribute to cementitious properties and GGBS replacement of fine aggregate further reduces porosity, increased replacement consistently increases carbonation resistance in case of the latter.

4.2.8 Period of Exposure for OPC Concrete

The results of the carbonation of the reference OPC concrete mixes, with W/C ratio varying over a range of 0.4 to 0.5 with 20, 60, 90, 120, 150 days period of exposure and cured for a period of 3 days, before exposing them to a rapid carbonation environment in the laboratory, as stated above, are given in table 4.8 and shown plotted in Figure 4.8

Table 4.8 Carbonation Depths of OPC Concrete Mixes for Various Periods of Exposure

Mix	W/C	Carbonation Depth (mm)				
		Period of Exposure (Days)				
		20	60	90	120	150
O_1	0.4	4.4	8.6	10.1	10.8	12.2
O_2	0.45	7.5	13.2	14.2	17.3	18.2
O_3	0.5	10.1	15.5	23.8	26.8	30.1

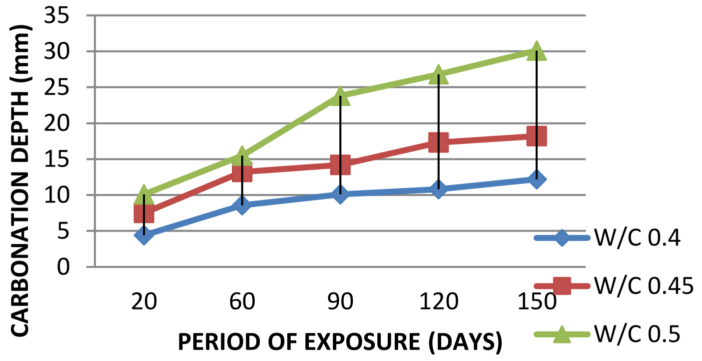


FIG.4.8 - Carbonation Depth vs. Period of Exposure for OPC Concrete

It can be observed from the above experimental results that for OPC concrete, the carbonation depth increases with the period of exposure. This indicates that the impact of carbonation progressively increases with time.

4.2.9 External Cover of OPC Concrete

The results of the carbonation of the reference OPC concrete mixes, with W/C ratio varying over a range of 0.4 to 0.5 for concrete and concrete with 12 mm plaster/acrylic emulsion paint and cured for a period of 3 days, before exposing them to a rapid carbonation environment in the laboratory, as stated above, are given in table 4.9 and shown plotted in Figure 4.9

Table 4.9 Carbonation Depth vs. OPC Concrete with/without Plaster and Paint

Mix	W/C	Carbonation Depth (mm)		
		Concrete	Concrete with 12 mm plaster	Concrete with 12 mm plaster and acrylic emulsion paint
O_1	0.4	4.4	3.2	2.5
O_2	0.45	7.5	5.5	4.8
O_3	0.5	10.1	7.2	5.2

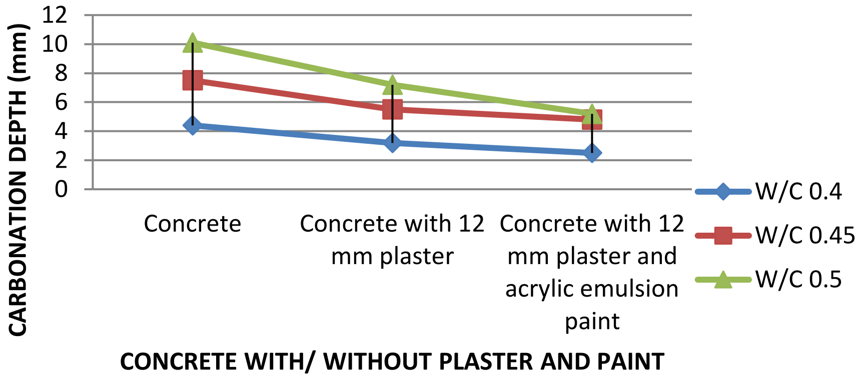


Fig.4.9 - Carbonation Depth vs OPC Concrete with/without Plaster and Paint

It can be seen from the above experimental results that for OPC concrete, carbonation depth reduces with increase in external protective cover. External covers like paint and plaster offer resistance to entry of deleterious materials and thus reduces the vulnerability of concrete to deterioration from carbonation.

4.2.10 PPC Concrete (Without Super Plasticizer)

The results of the carbonation of the reference PPC concrete mixes, with W/C ratio varying over a range of 0.4 to 0.5 and cured for a period of 3, 7, 21, 28 and 56 days, before exposing them to a rapid carbonation environment in the laboratory, as stated above, are given in table 4.10 and shown plotted in Figure 4.10

Table 4.10 Carbonation Depth of PPC Concrete Mixes (Without Super Plasticizer)

Mix	W/C	Carbonation Depth (mm)				
		Period of Curing (Days)				
		3	7	21	28	56
P_1	0.4	8.2	7.4	7.3	7.1	6.8
P_2	0.45	14.1	12.7	12.1	11.8	11.6
P_3	0.5	18.8	16.8	16.2	15.8	15.2

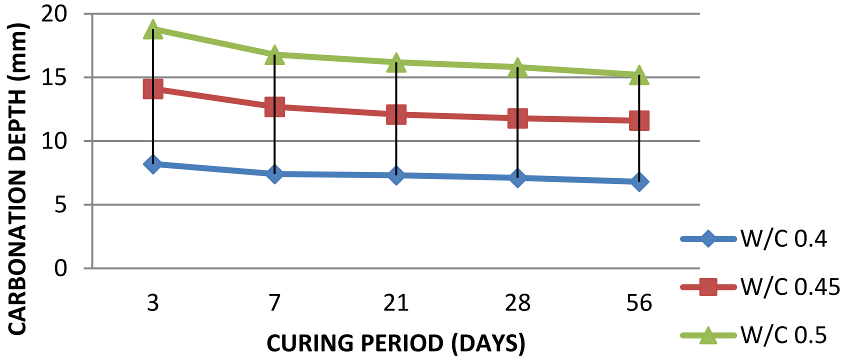


FIG.4.10- Carbonation Depth of PPC Concete at Various Curing Periods

It is evident from test results that carbonation depth in PPC concrete increases with increase in water cement ratio and that carbonation depth decreases as the curing period increases, as already seen in case of OPC concrete also.

It is also observed that the depths of carbonation in PPC concrete are higher than that of OPC concrete. The addition of SCM to clinker in case of PPC reduces the Clinker content in PPC thus lowering the available content of $Ca(OH)_2$. As a result, less CH content is available for hydration to $CaCO_3$. $CaCO_3$ being voluminous compound that contributes to reduction in pore space plays a major role in porosity of concrete. Thus formation of comparatively less volume of $CaCO_3$ in PPC results in more porous concrete facilitating higher ingress of CO_2 and thus increased carbonation.

4.2.11 PPC Concrete (With Super Plasticizer)

The results of the carbonation of the reference PPC concrete mixes, with W/C ratio varying over a range of 0.4 to 0.5 and cured for a period of 3, 7, 21, 28 and 56 days, before exposing them to a rapid carbonation environment in the laboratory, as stated above, are given in table 4.11 and shown plotted in Figure 4.11

Table 4.11 Carbonation Depth of PPC Concrete Mixes (With Super Plasticizer)

Mix	W/C	Carbonation Depth (mm)				
		Period of Curing (Days)				
		3	7	21	28	56
PS_1	0.4	6.8	6.7	6.5	6.3	6.1
PS_2	0.45	11.5	11.1	10.6	10.3	10.1
PS_3	0.5	16	15.2	14.1	13.4	13.2

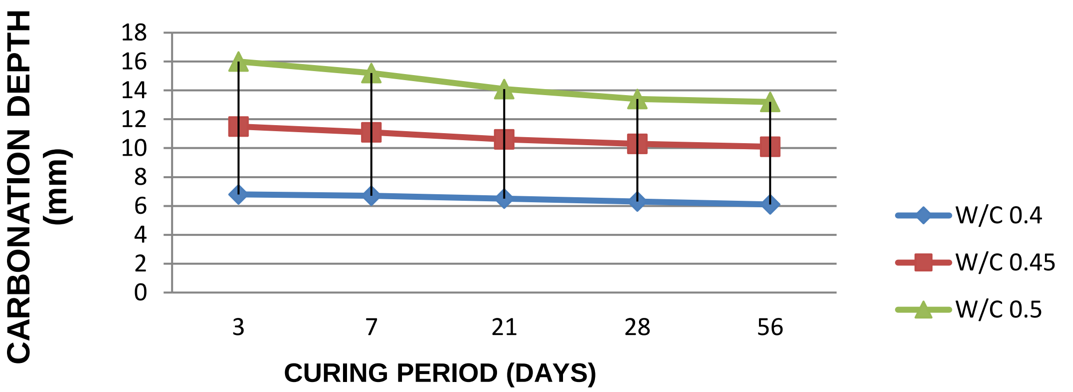


FIG.4.11 - Carbonation Depth of PPC Concrete Using Super Plasticizer at Various Curing Periods

It can be established from the above results that carbonation depth increases with increase in water cement ratio and that carbonation depth decreases with increasing curing period as well as the fact that carbonation in PPC concrete is higher than that in OPC concrete. It can also be seen from the above experimental data that use of super plasticizer reduces the effect of carbonation in concrete just as that in OPC as observed above.

4.2.12 PPC Concrete with Fly Ash Replacement of Cement

The results of the carbonation of the reference PPC concrete mixes, with W/C ratio varying over a range of 0.4 to 0.5, with10, 30, 50 and 70% replacement of cement with fly ash and cured for a period of 3 days, before exposing them to a rapid carbonation environment in the laboratory, as stated above, are given in table 4.12 and shown plotted in Figure 4.12

Table 4.12 Carbonation Depth of PPC Concrete Mixes with Fly Ash Replacement of Cement

W/C	Percentage Replacement	Mix	Carbonation Depth (mm)
0.4	No replacement of cement	P_1	8.2
	10 % replacement of cement with Fly Ash	PF_3	7.2
	30 % replacement of cement with Fly Ash	PF_6	8.4
	50 % replacement of cement with Fly Ash	PF_9	8.5
	70 % replacement of cement with Fly Ash	PF_{12}	8.6
0.45	No replacement of cement	P_2	14.1
	10 % replacement of cement with Fly Ash	PF_2	12.1
	30 % replacement of cement with Fly Ash	PF_5	14.8
	50 % replacement of cement with Fly Ash	PF_8	15.2
	70 % replacement of cement with Fly Ash	PF_{11}	15.3
0.5	No replacement of cement	P_3	18.8
	10 % replacement of cement with Fly Ash	PF_1	17.4
	30 % replacement of cement with Fly Ash	PF_4	22.1
	50 % replacement of cement with Fly Ash	PF_7	23
	70 % replacement of cement with Fly Ash	PF_{10}	23.2

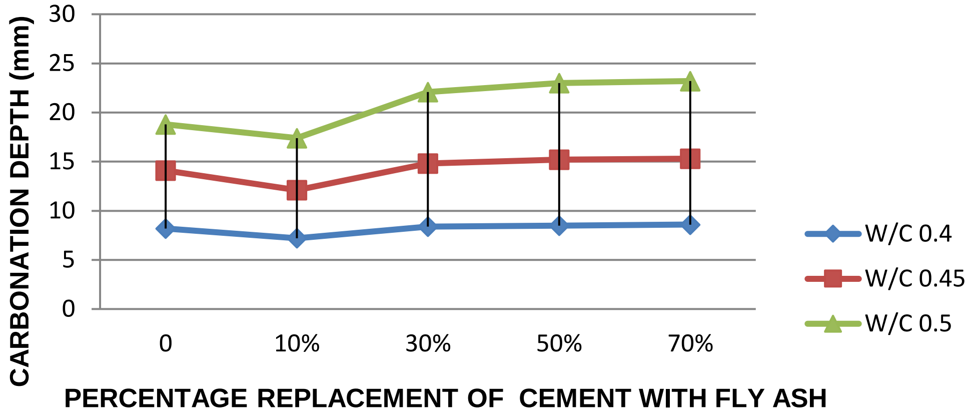


FIG.4.12 - Carbonation Depth of PPC Concrete with Fly Ash replacement of cement

It can be observed from test results that for PPC concrete also, depth of carbonation initially reduces up to 10 % replacement of cement with FA. However, increase in percentage replacement of cement with FA results in an increase of carbonation for similar reasons as observed in case of OPC concrete above.

4.2.13 PPC Concrete with Micro Silica Replacement of Cement

The results of the carbonation of the reference PPC concrete mixes, with W/C ratio varying over a range of 0.4 to 0.5, with 10, 30, 50 and 70% replacement of cement with micro silica and cured for a period of 3 days, before exposing them to a rapid carbonation environment in the laboratory, as stated above, are given in table 4.13 and shown plotted in Figure 4.13

Table 4.13 Carbonation Depth of PPC Concrete Mixes with Micro Silica Replacement of Cement

W/C	Percentage Replacement	Mix	Carbonation Depth (mm)
0.4	No replacement of cement	P_1	8.2
	10 % replacement of cement with Micro silica	PM_3	5.8
	30 % replacement of cement with Micro silica	PM_6	10.1
	50 % replacement of cement with Micro silica	PM_9	11.2
	70 % replacement of cement with Micro silica	PM_{12}	11.4

0.45	No replacement of cement	P_2	14.1
	10 % replacement of cement with Micro silica	PM_2	10.1
	30 % replacement of cement with Micro silica	PM_5	17.4
	50 % replacement of cement with Micro silica	PM_8	18.7
	70 % replacement of cement with Micro silica	PM_{11}	19.5
0.5	No replacement of cement	P_3	18.8
	10 % replacement of cement with Micro silica	PM_1	15.1
	30 % replacement of cement with Micro silica	PM_4	23.5
	50 % replacement of cement with Micro silica	PM_7	24.5
	70 % replacement of cement with Micro silica	PM_{10}	25.9

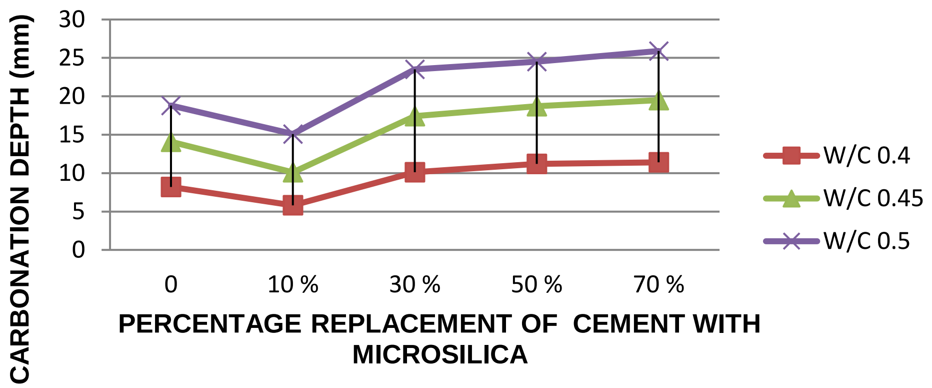


FIG.4.13 - Carbonation Depth of PPC Concrete with Micro Silica Replacement of Cement

It can be observed from test results that for PPC concrete also, depth of carbonation initially reduces up to 10 % replacement of cement with micro silica. However, increase in percentage replacement of cement with micro silica results in an increase of carbonation for reasons as observed in case of OPC concrete above.

4.2.14 PPC Concrete with Fly Ash Replacement of Fine Aggregate

The results of the carbonation of the reference PPC concrete mixes, with W/C ratio varying over a range of 0.4 to 0.5, with 10, 30, 50 and 70% replacement of fine aggregate with fly ash and cured for a period of 3 days, before exposing them to a rapid carbonation environment in the laboratory, as stated above, are given in table 4.14 and shown plotted in Figure 4.14

Table 4.14 Carbonation Depth of PPC Concrete Mixes with Fly Ash Replacement of Fine Aggregate

W/C	Percentage Replacement	Mix	Carbonation Depth (mm)
	No replacement of Fine aggregate	P_1	8.2
	10 % replacement of Fine aggregate with Fly Ash	PFF_3	6.2
0.4	30 % replacement of Fine aggregate with Fly Ash	PFF_6	5.8
	50 % replacement of Fine aggregate with Fly Ash	PFF_9	5.4
	70 % replacement of Fine aggregate with Fly Ash	PFF_{12}	5.3
	No replacement of Fine aggregate	P_2	14.1
	10 % replacement of Fine aggregate with Fly Ash	PFF_2	11.2
0.45	30 % replacement of Fine aggregate with Fly Ash	PFF_5	10.8
	50 % replacement of Fine aggregate with Fly Ash	PFF_8	10.1
	70 % replacement of Fine aggregate with Fly Ash	PFF_{11}	9.7
	No replacement of Fine aggregate	P_3	18.8
	10 % replacement of Fine aggregate with Fly Ash	PFF_1	14.2
0.5	30 % replacement of Fine aggregate with Fly Ash	PFF_4	13.1
	50 % replacement of Fine aggregate with Fly Ash	PFF_7	12.2
	70 % replacement of Fine aggregate with Fly Ash	PFF_{10}	11.9

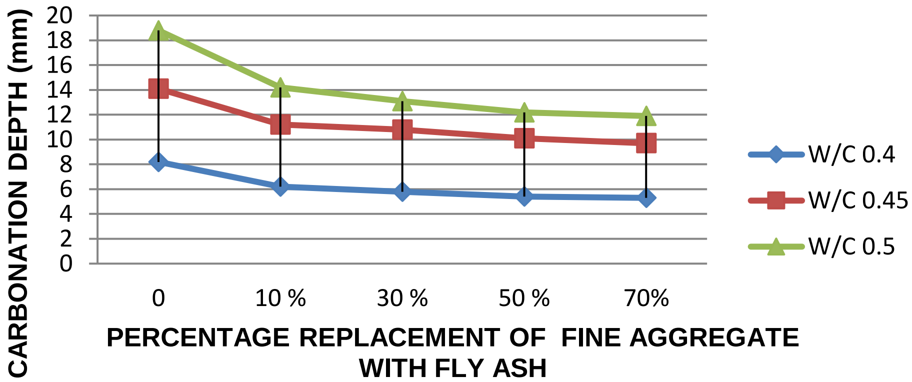


FIG.4.14 - Carbonation Depth of PPC Concrete with Fly Ash Replacement of Fine Aggregate

It can be observed from the above test results that for PPC concrete, depths of carbonation decreases with increase in percentage replacement of fine aggregate with FA. It may be noted that results of cement replacement and fine aggregate replacement with FA do not follow the same pattern.

4.2.15 PPC Concrete with GGBS Replacement of Cement

The results of the carbonation of the reference PPC concrete mixes, with W/C ratio varying over a range of 0.4 to 0.5, with10, 30, 50 and 70% replacement of cement with GGBS and cured for a period of 3 days, before exposing them to a rapid carbonation environment in the laboratory, as stated above, are given in table 4.15 and shown plotted in Figure 4.15

Table 4.15 Carbonation Depth of PPC Concrete Mixes with GGBS Replacement of Cement

W/C	Percentage Replacement	Mix	Carbonation Depth (mm)
0.4	No replacement of cement	P1	8.2
	10 % replacement of cement with GGBS	PG3	7
	30 % replacement of cement with GGBS	PG6	6.5
	50 % replacement of cement with GGBS	PG9	8.4
	70 % replacement of cement with GGBS	PG12	8.6
0.45	No replacement of cement	P2	14.1
	10 % replacement of cement with GGBS	PG2	12
	30 % replacement of cement with GGBS	PG5	11.7
	50 % replacement of cement with GGBS	PG8	15
	70 % replacement of cement with GGBS	PG11	15.5
0.5	No replacement of cement	P3	18.8
	10 % replacement of cement with GGBS	PG1	17.3
	30 % replacement of cement with GGBS	PG4	16.9
	50 % replacement of cement with GGBS	PG7	22.5
	70 % replacement of cement with GGBS	PG10	23

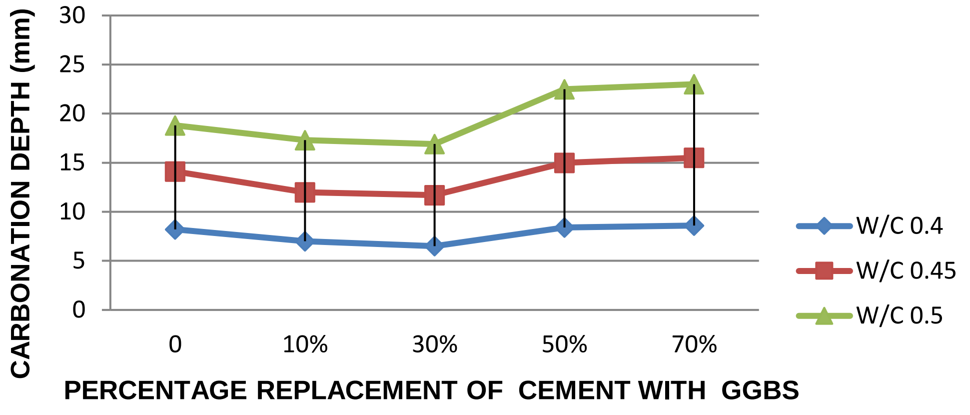


FIG.4.15 - Carbonation Depth of PPC Concrete with GGBS Replacement of Cement

It can be observed from the above test results that for PPC concrete, carbonation depth initially decrease up to 30 % replacement of cement with GGBS and subsequently increases on increasing percentage replacement due to similar reasons as observed in case of OPC concrete above.

4.2.16 PPC Concrete with GGBS Replacement of Fine Aggregate

The results of the carbonation of the reference PPC concrete mixes, with W/C ratio varying over a range of 0.4 to 0.5, with10, 30, 50 and 70% replacement of fine aggregate with GGBS and cured for a period of 3 days, before exposing them to a rapid carbonation environment in the laboratory, as stated above, are given in table 4.16 and shown plotted in Figure 4.16

Table 4.16 Carbonation Depth of PPC Concrete Mixes with GGBS replacement of Fine Aggregate

W/C	Percentage Replacement	Mix	Carbonation Depth (mm)
0.4	No replacement of Fine aggregate	P1	8.2
	10 % replacement of Fine aggregate with GGBS	PFG3	6.2
	30 % replacement of Fine aggregate with GGBS	PFG6	5.9
	50 % replacement of Fine aggregate with GGBS	PFG9	5.5
	70 % replacement of Fine aggregate with GGBS	PFG12	5.2

0.45	No replacement of Fine aggregate	P2	14.1
	10 % replacement of Fine aggregate with GGBS	PFG2	11
	30 % replacement of Fine aggregate with GGBS	PFG5	10.6
	50 % replacement of Fine aggregate with GGBS	PFG8	10
	70 % replacement of Fine aggregate with GGBS	PFG11	9.8
0.5	No replacement of Fine aggregate	P3	18.8
	10 % replacement of Fine aggregate with GGBS	PFG1	14
	30 % replacement of Fine aggregate with GGBS	PFG4	12.8
	50 % replacement of Fine aggregate with GGBS	PFG7	12
	70 % replacement of Fine aggregate with GGBS	PFG10	11.7

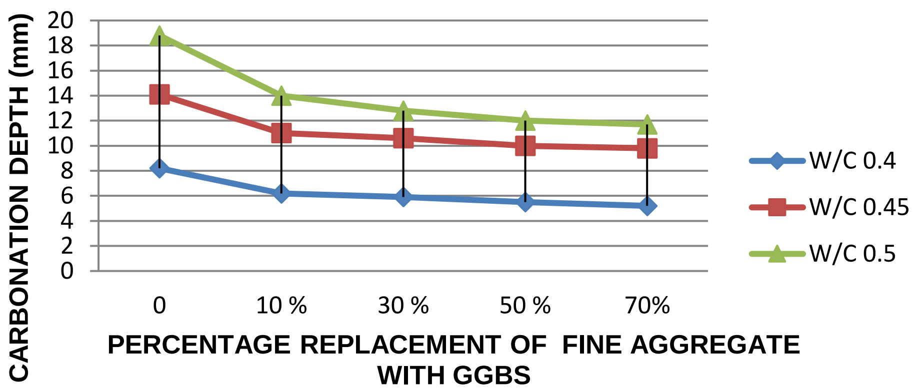


FIG.4.16 - Carbonation Depth of PPC Concrete WITH GGBS Replacement of Fine Aggregate

It can be observed that for PPC concrete also, carbonation reduces with increase in percentage replacement of fine aggregate with GGBS for similar reasons explained in case of OPC concrete above.

4.2.17 Period of Exposure of PPC Concrete

The results of the carbonation of the reference OPC concrete mixes, with W/C ratio varying over a range of 0.4 to 0.5 with 20, 60, 90, 120 and 150 days period of exposure and cured for a period of 3 days, before exposing them to a rapid carbonation environment in the laboratory, as stated above, are given in table 4.17 and shown plotted in Figure 4.17

Table 4.17 Carbonation Depth of PPC Concrete Mixes for Various Periods of Exposure

Mix	W/C	Carbonation Depth (mm)				
		Period of Exposure (Days)				
		10	20	30	40	50
P_1	0.4	5.4	8.2	10.4	11.2	12.9
P_2	0.45	9.1	14.1	16.9	18.8	20.3
P_3	0.5	12.9	18.8	25.9	27.8	32.6

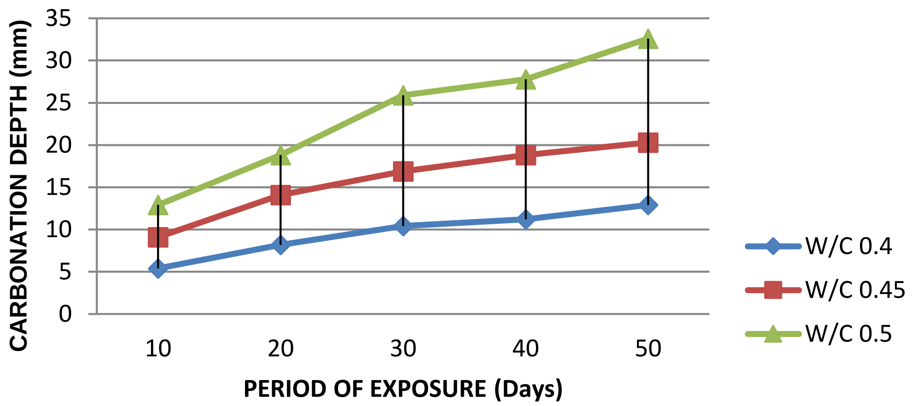


FIG.4.17 - Carbonation Depth vs. Periods of Exposures at Variable W/C for PPC Concrete

It can be seen from the above experimental results that for PPC concrete also, carbonation depth increases with increase in period of exposure.

4.2.18 External Cover of PPC Concrete

The results of the carbonation of the reference PPC concrete mixes, with W/C ratio varying over a range of 0.4 to 0.5 for 12mm plaster and acrylic emulsion paint and cured for a period of 3 days, before exposing them to a rapid carbonation environment in the laboratory, as stated above, are given in table 4.18 and shown plotted in Figure 4.1

Table 4.18 Carbonation Depth vs. PPC Concrete with/without Plaster and Paint

Mix	W/C	Concrete	Concrete with 12 mm Plaster	Concrete with 12 mm Plaster and Acrylic Emulsion Paint
O_1	0.4	8.2	6.8	5.9
O_2	0.45	14.1	11.1	9.5
O_3	0.5	18.8	14.8	11.8

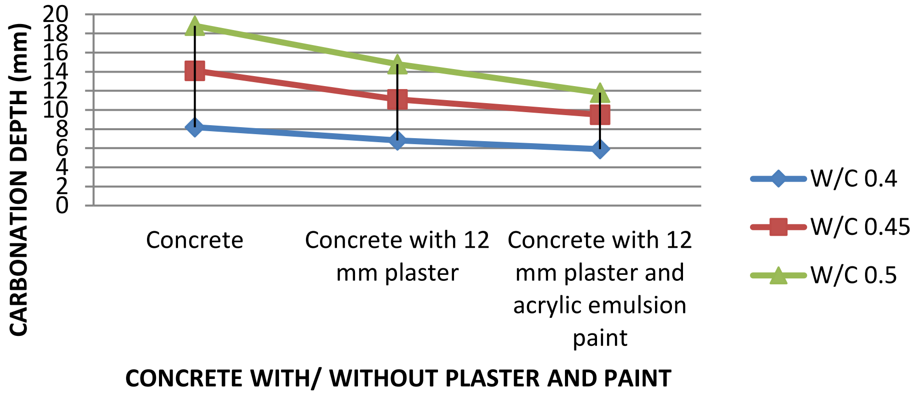


Fig.4.18 - Carbonation Depth vs PPC Concrete with/without Plaster and Paint

It can be seen from the above experimental results that for PPC concrete also, carbonation depth reduces with increase in external protective covers like paint and plaster which offer resistance to entry of deleterious materials and thus reduces the vulnerability of concrete to deterioration from carbonation.

4.3 Carbonation Depth from Phenolphthalein Indicator at Variable Parameters

4.3.1 CO_2 Concentration on OPC Concrete

The results of the carbonation of the reference OPC concrete mixes, with W/C ratio varying over a range of 0.4 to 0.5 with 4,10,20,30 and 50 % of $CO_2$and cured for a period of 3 days, before exposing them to a rapid carbonation environment in the laboratory, as stated above, are given in table 4.19 and shown plotted in Figure 4.19

Table 4.19 Carbonation Depth of OPC Concrete Mixes for various percentages of CO_2

Mix	W/C	Carbonation Depth (mm)				
		Percentage of CO_2 (%)				
		4	10	20	30	50
O_1	0.4	4.4	7.5	9.9	12.1	17.8
O_2	0.45	7.5	11.8	16.3	20.6	26.7
O_3	0.5	10.1	16.1	21.6	27.5	34.1

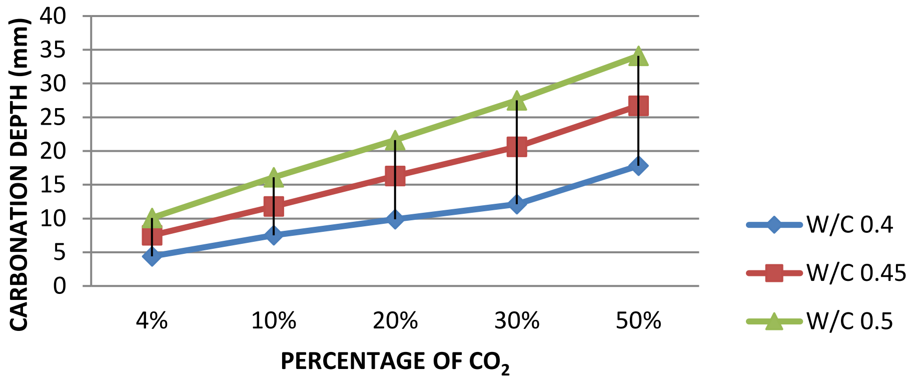


Fig.4.19 - Carbonation Depth vs. Percentage of CO_2 at Variable W/C for OPC Concrete

It can be seen from the experimental results above that for OPC concrete, carbonation depth increases with increase in percentage of CO_2 concentration. This indicates that rate of carbonation depends on the rate of diffusion of CO_2 into the concrete sample.

4.3.2 CO_2 Concentration on PPC Concrete

The results of the carbonation of the reference PPC concrete mixes, with W/C ratio varying over a range of 0.4 to 0.5 with 4, 10, 20, 30 and 50 % of CO_2 and cured for a period of 3 days, before exposing them to a rapid carbonation environment in the laboratory, as stated above, are given in table 4.20 and shown plotted in Figure 4.20

Table 4.20 Carbonation Depth of PPC Concrete Mixes for Various Percentages of CO_2

Mix	W/C	Carbonation Depth (mm)				
		Percentage of CO_2 (%)				
		4	10	20	30	50
P_1	0.4	8.2	11	19.4	20.5	31.1
P_2	0.45	14.1	20.2	35.5	42.1	55.6
P_3	0.5	18.8	35.2	45.1	50.6	70.1

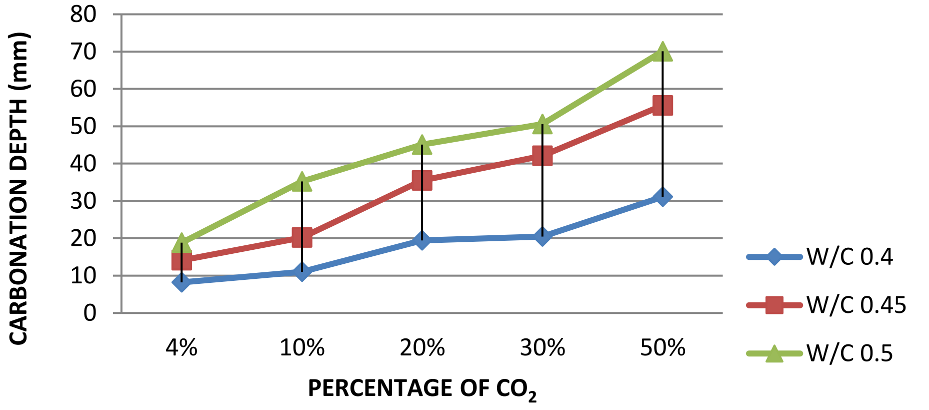


FIG.4.20 - Carbonation Depth vs. Percentage of CO_2 at Variable W/C for PPC Concrete

It can be seen that for PPC concrete also, carbonation depth increases with increase in percentage of CO_2 concentration for reasons cited above.

4.3.3 Relative Humidity on OPC Concrete

The results of the carbonation of the reference OPC concrete mixes, with W/C ratio varying over a range of 0.4 to 0.5 with 40, 50, 65, 85 and 100 % of Relative Humidity and cured for a period of 3 days, before exposing them to a rapid carbonation environment in the laboratory, as stated above, are given in table 4.21 and shown plotted in Figure 4.21

Table 4.21 Carbonation Depth of OPC Concrete Mixes for Various Percentages of Relative Humidity

Mix	W/C	Carbonation Depth (mm)				
		Percentage of Relative Humidity (%)				
		40	50	65	85	100
O_1	0.4	3.9	4.1	4.4	4.4	4.2
O_2	0.45	6.5	6.9	7.5	7.5	6.5
O_3	0.5	9.2	9.5	10.1	10.2	9.1

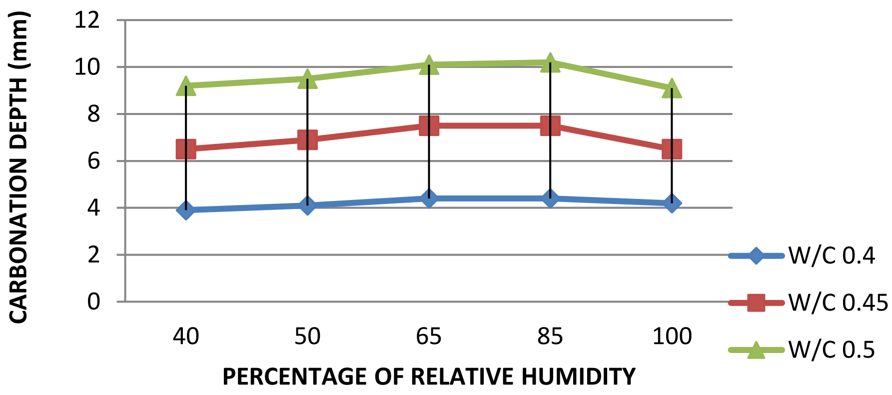


FIG.4.21- Carbonation Depth vs. Percentage of Relative Humidity at Variable W/C for OPC Concrete

It can be seen that for OPC concrete, carbonation initially increases with an increase in RH up to 85 % and then subsequently decreases with increase of RH. The increase in RH increases the moisture content and fluidity of particles as well as transportation of CO_2 within the pores thus facilitating progressive carbonation. However, after 85 % RH, the pores are fully saturated with moisture and thus resist the transportation of CO_2 through the pores.

4.2.4 Relative Humidity on PPC Concrete

The results of the carbonation of the reference PPC concrete mixes, with W/C ratio varying over a range of 0.4 to 0.5 with 40, 50, 65, 85 and 100 % of Relative Humidity and cured for a period of 3 days, before exposing them to a rapid carbonation environment in the laboratory, as stated above, are given in table 4.22 and shown plotted in Figure 4.22

Table 4.22 Carbonation Depth of PPC Concrete Mixes for Various Percentages of Relative Humidity

Mix	W/C	Carbonation Depth (mm)				
		Percentage of Relative Humidity (%)				
		40	50	65	85	100
P_1	0.4	7.1	7.9	8.2	8.21	7.6
P_2	0.45	10	12.7	14.1	14.5	12.2
P_3	0.5	14.2	17.6	18.8	19.1	15.2

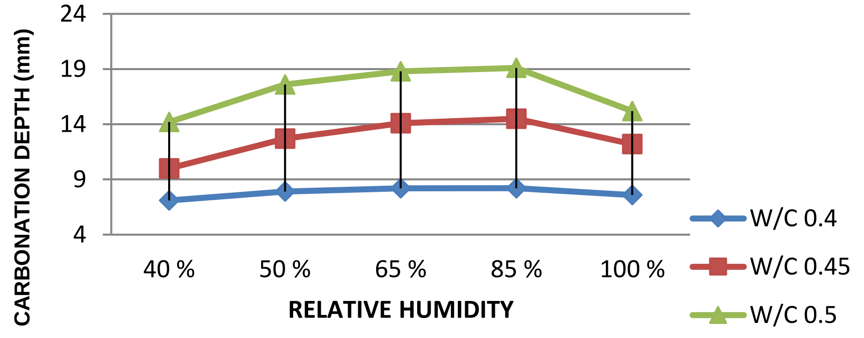


FIG.4.22 - Carbonation Depth vs. Percentage of Relative Humidity for PPC Concrete

It can be seen that for PPC concrete also, carbonation initially increases with an increase in RH up to 85 % and then subsequently decreases with increase of RH for reasons cited above.

4.4 Carbonation Depth from XRD Analysis

The $CaCO_3$ peak lies in the 2ϴ value of (29.37). The same also confirms to JCPDS pdf no. 72-1937.

Carbonation depth is obtained by X- Ray diffraction pattern at different depths of concrete cubes. A significant reduction in peak height of $CaCO_3$ can be observed with increasing the depth of sample.

Fig. 4.23 to 4.28 shows XRD Graph between intensity and diffraction angle (2ϴ) of different types of concrete at 3 days curing period, 4 % CO_2 concentration and 65 % relative humidity and retention period of 20 days in carbonation chamber for both OPC and PPC concrete. Q represents peak value of intensity for quartz (SiO_2) and C represents peak value of intensity for $CaCO_3$. The presence of peak value for $CaCO_3$ in the graphs indicate carbonation at given depths while the absence of peak indicates no carbonation at the given depth since $CaCO_3$ which is a resultant of carbonation is not present at that depth.

4.4.1 OPC Concrete with W/C 0.4

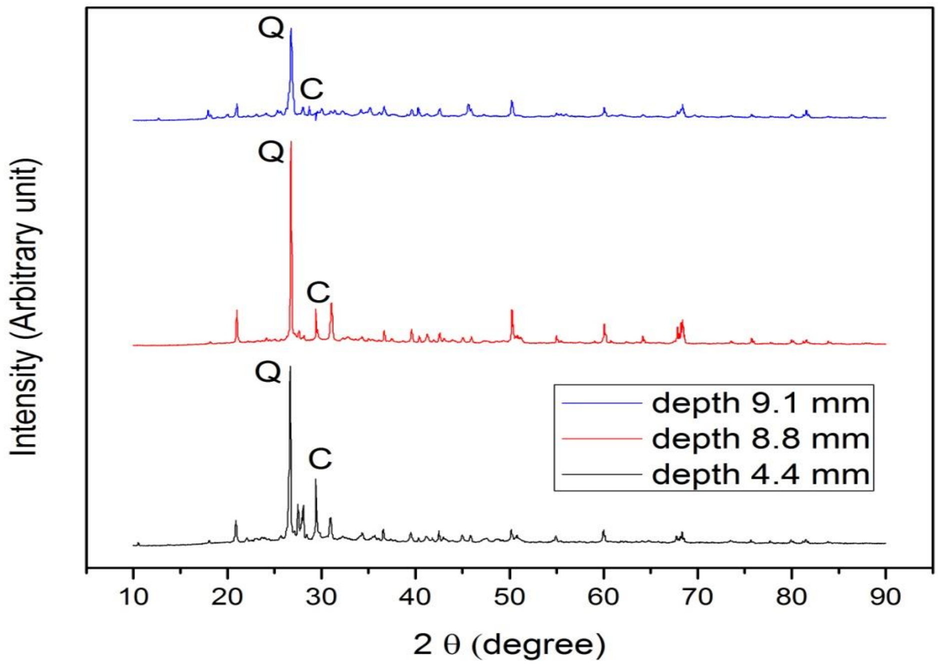


Fig 4.23 XRD RESULTS FOR OPC CONCRETE AT W/C 0.4

A study of XRD analysis of sliced concrete samples randomly at depths 4.4 mm, 8.8 mm and 9.1 mm for 2ϴ values corresponding to $CaCO_3$ (C) and SiO_2 (Q) represented in Figure 4.23 above reveals that the peak value of intensity for 2ϴ values corresponding to $CaCO_3$ is observed in graphs at 4.4. mm sample and 8.8 mm sample but not in 9.1 mm sample. The presence of peak values of intensity at 2ϴ values corresponding to $CaCO_3$ indicates the presence of the compound formed as a result of carbonation at that depth. The absence of peak value at 9.1 mm indicates absence of $CaCO_3$ at that depth which indicates that carbonation has not taken place at that particular depth.

Thus depth of carbonation can be ascertained as 8.8 mm.

4.4.2 OPC Concrete with W/C 0.45

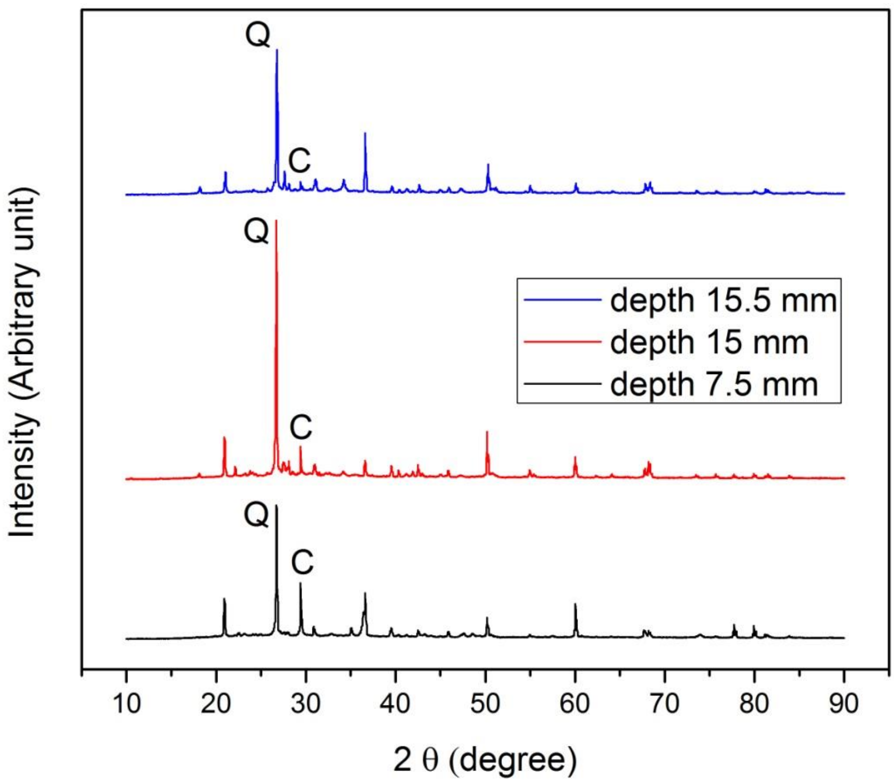


Fig 4.24 XRD RESULTS FOR OPC CONCRETE AT W/C 0.45

A study of XRD analysis of sliced concrete samples randomly at depths 7.5 mm, 15.0 mm and 15.5 mm for 2ϴ values corresponding to $CaCO_3$ (C) and SiO_2 (Q) represented in Figure 4.24 above reveals that the peak value of intensity for 2ϴ values corresponding to $CaCO_3$ is observed in graphs at 7.5 mm sample and 15.0 mm sample while extremely small peak is observed at 15.5 mm. Thus it can be inferred that depth of carbonation lies between 15.0 mm and 15.5 mm i.e. approximately 15.2 mm.

4.4.3 OPC Concrete with W/C 0.5

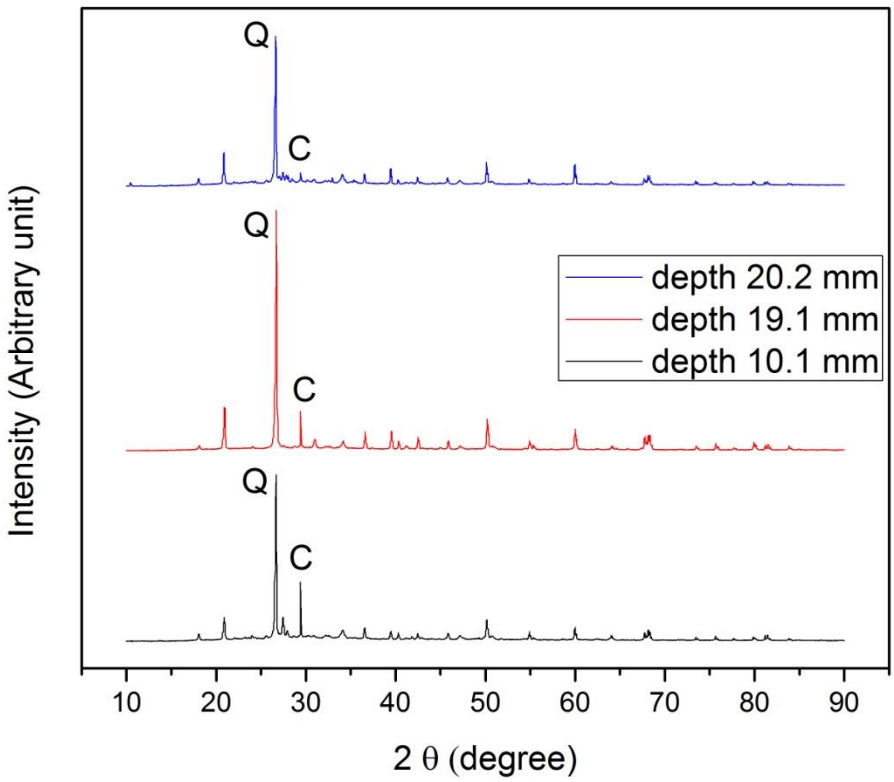


Fig 4.25 XRD RESULTS FOR OPC CONCRETE AT W/C 0.5

A study of XRD analysis of sliced concrete samples randomly at depths 10.1 mm, 19.1 mm and 20.2 mm for 2ϴ values corresponding to $CaCO_3$ (C) and SiO_2 (Q) represented in

Figure 4.25 above reveals that the peak value of intensity for 2Ө values corresponding to CaCO3 is observed in graphs at 10.1 mm sample and 19.1 mm sample while extremely small peak is observed at 20.2 mm. Thus it can be inferred that depth of carbonation is approximately 19.4 mm.

4.4.4 PPC Concrete with W/C 0.4

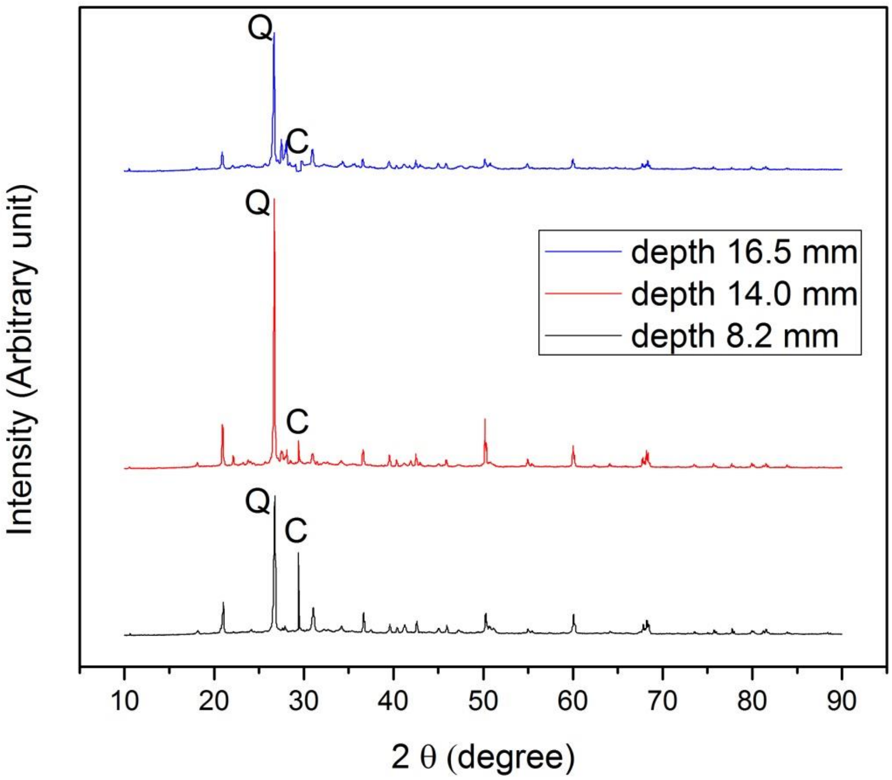


Fig 4.26 XRD RESULTS FOR PPC CONCRETE AT W/C 0.4

A study of XRD analysis of sliced concrete samples randomly at depths 8.2 mm, 14.0 mm and 16.5 mm for 2Ө values corresponding to CaCO3 (C) and SiO2 (Q) represented in Figure 4.26 above reveals that the peak value of intensity for 2Ө values corresponding to CaCO3 is observed in graphs at 8.2 mm sample and 14.0 mm sample but not in 16.5 mm sample. Thus depth of carbonation can be ascertained as 14.0 mm.

4.4.5 PPC Concrete with W/C 0.45

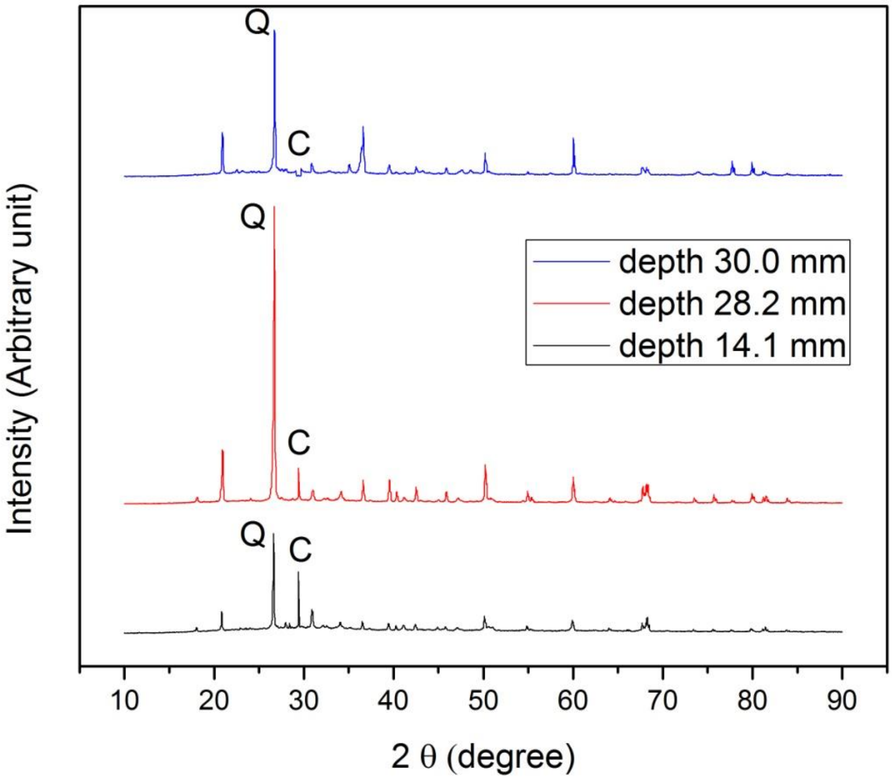


Fig 4.27 XRD RESULTS FOR PPC CONCRETE AT W/C 0.45

A study of XRD analysis of sliced concrete samples randomly at depths 14.1 mm, 28.2 mm and 30.0 mm for 2ϴ values corresponding to CaCO3 (C) and SiO2 (Q) represented in Figure 4.27 above reveals that the peak value of intensity for 2ϴ values corresponding to $CaCO_3$ is observed in graphs at 14.1 mm sample and 28.2 mm sample but not in 30.0 mm sample. Thus depth of carbonation can be ascertained as 28.2 mm.

4.4.6 PPC Concrete with W/C 0.5

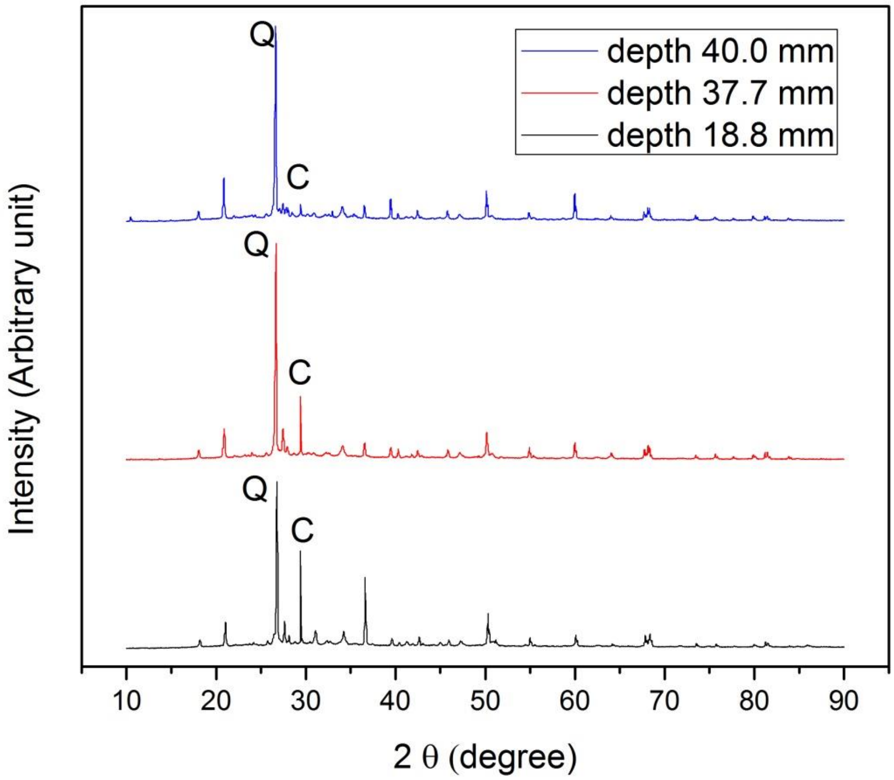


Fig 4.28 XRD RESULTS FOR PPC CONCRETE AT W/C 0.5

A study of XRD analysis of sliced concrete samples randomly at depths 18.8 mm, 37.7 mm and 40.0 mm for 2ϴ values corresponding to CaCO3 (C) and SiO2 (Q) represented in Figure 4.25 above reveals that the peak value of intensity for 2ϴ values corresponding to $CaCO_3$ is observed in graphs at 18.8 mm sample and 37.7 mm sample while extremely small peak is observed at 40.0 mm. Thus depth of carbonation lies between 37.7 mm and 40.0 mm. It can be inferred that depth of carbonation is 38.8 mm.

4.5 Results Obtained From FTIR Method

In FTIR method, Carbonation depth can be derived from a study of the characteristic peak of the C-O functional group in the wavenumber range of 1410-1510 cm^{-1}. Carbonation depth is determined from the position of the C-O characteristic peaks relative to the baseline. Graphs between absorbance and wavenumber for different type of concrete with different W/C at 3 days curing period, 4 % CO_2 concentration and 65 % relative humidity and retention period of 20 days in carbonation chamber for both OPC and PPC concrete are shown in Fig. 4.29 to Fig. 4.34 and the depth of carbonation is derived with reference to a baseline at 37 % transmittance as per Chang et al (2006). Peaks lying below the baseline indicate depth of carbonation.

4.5.1 OPC Concrete with W/C 0.4

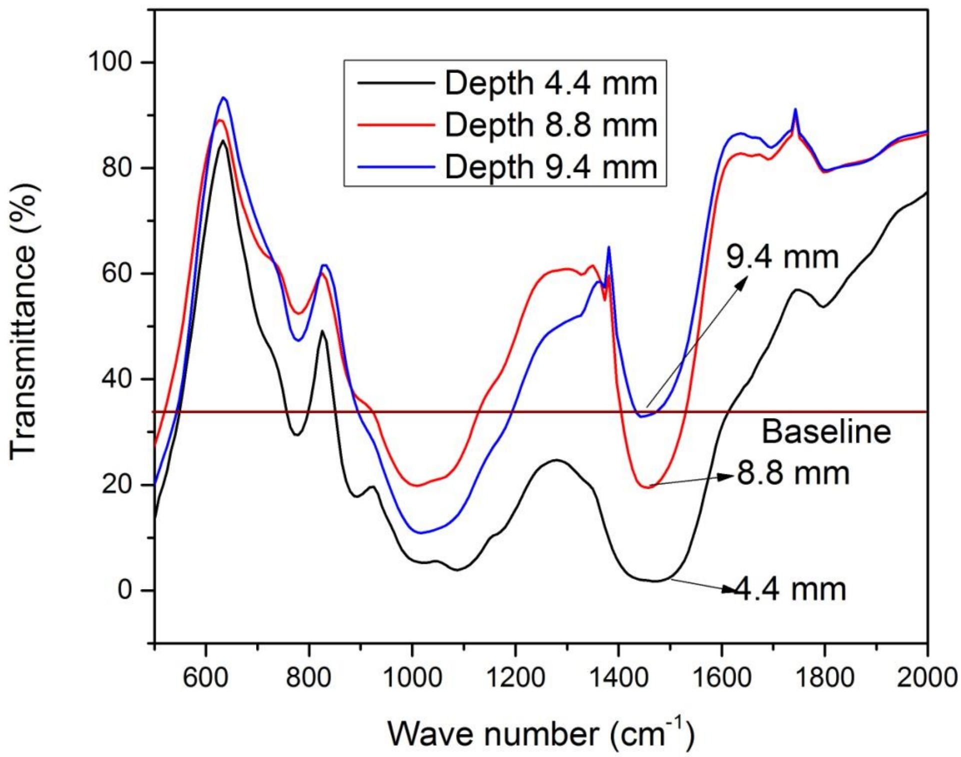


Fig 4.29 FTIR RESULTS FOR OPC CONCRETE AT W/C 0.4

From Figure 4.29 it can be inferred that depth of carbonation in concrete sample of OPC cement with 0.4 W/C is 9.4 mm, since the trough values lying in the range of Wave number 1410-1510 cm^{-1} falls below the base line for each of the graphs pertaining to depths of 4.4 mm, 8.8 mm and 9.4 mm. Since 9.4 mm just lies at the baseline, depth of carbonation is concluded at 9.4 mm.

4.5.2 OPC Concrete with W/C 0.45

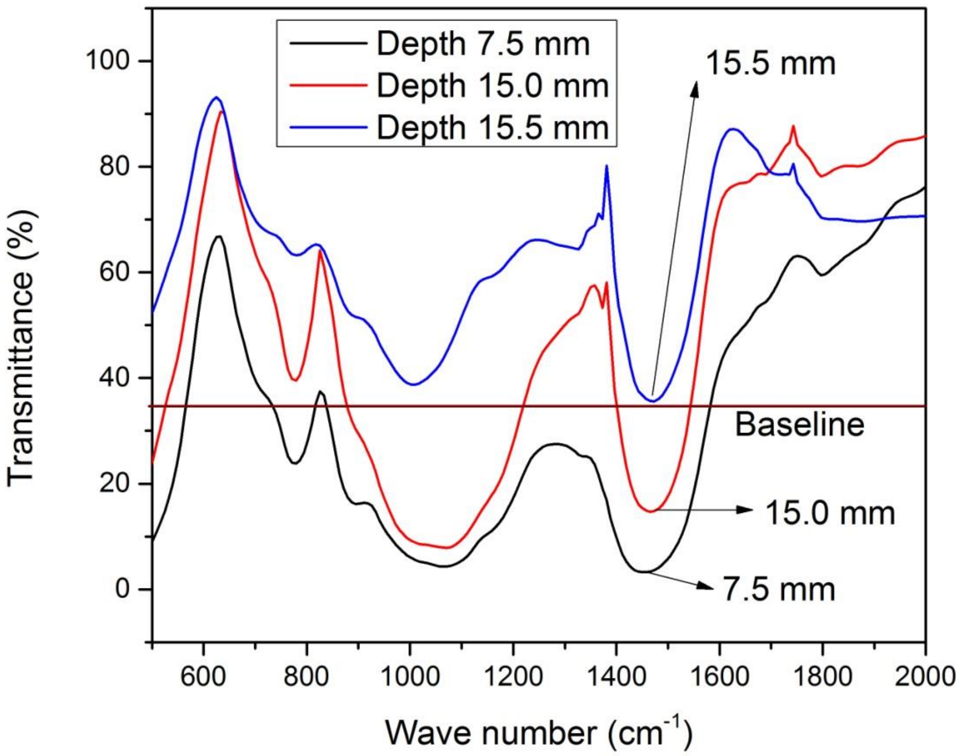


Fig 4.30 FTIR RESULTS FOR OPC CONCRETE AT W/C 0.45

From Figure 4.30 it can be inferred that depth of carbonation in concrete sample of OPC cement with 0.45 W/C is 15.3 mm, since the trough values lying in the range of Wave number 1410-1510 cm^{-1}falls below the base line for each of the graphs pertaining to depths of 7.5 mm and 15.0 mm and lies just above the baseline for the graph pertaining to 15.5 mm. Hence, it is inferred that the depth of carbonation is 15.3 mm.

4.5.3 OPC Concrete with W/C 0.5

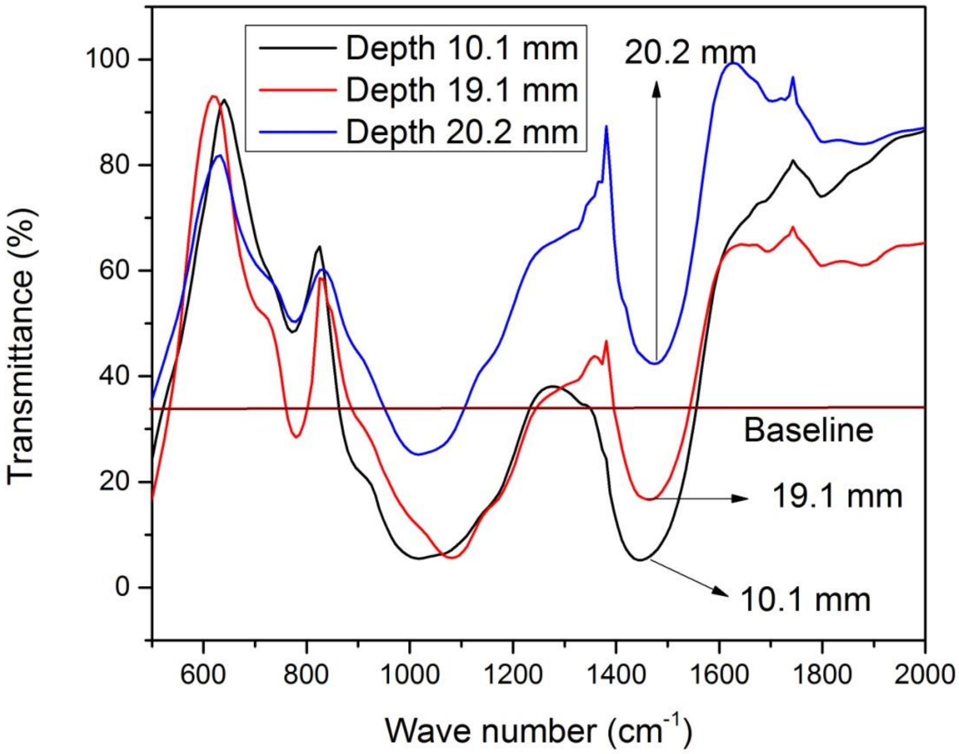


Fig 4.31 FTIR RESULTS FOR OPC CONCRETE AT W/C 0.5

From Figure 4.31 it can be inferred that depth of carbonation in concrete sample of OPC cement with 0.5 W/C is 19.7 mm, since the trough values lying in the range of Wave number 1410-1510 cm^{-1}falls below the base line for each of the graphs pertaining to depths of 10.1 mm and 19.1 mm and lies above the baseline for 20.2 mm. Since the baseline is in between the graphs for 19.1 mm and 20.2 mm, it can be inferred that depth of carbonation is 19.7 mm.

4.5.4 PPC Concrete with W/C 0.4

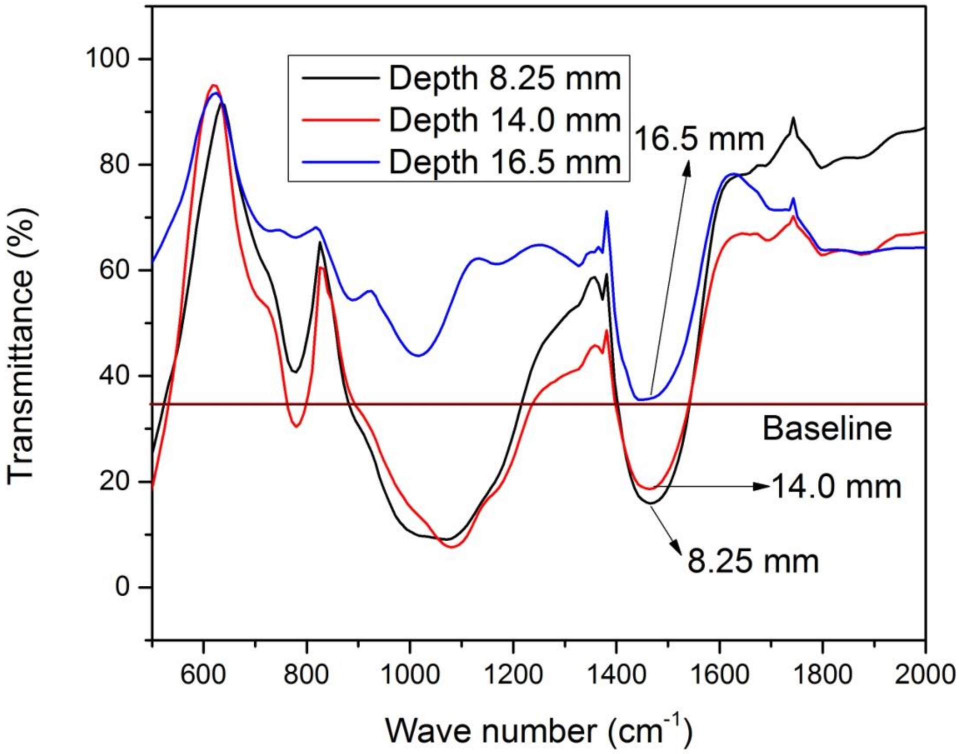


Fig 4.32 FTIR RESULTS FOR PPC CONCRETE AT W/C 0.4

From Figure 4.32 it can be inferred that depth of carbonation in concrete sample of PPC cement with 0.4 W/C is 16.3 mm, since the trough values lying in the range of Wave number 1410-1510 cm^{-1}falls below the base line for each of the graphs pertaining to depths of 8.25 mm and 14.0 mm and lies just above the baseline for the graph pertaining to 16.5 mm. Hence, it can be inferred that the depth of carbonation is 16.3 mm.

4.5.5 PPC Concrete with W/C 0.45

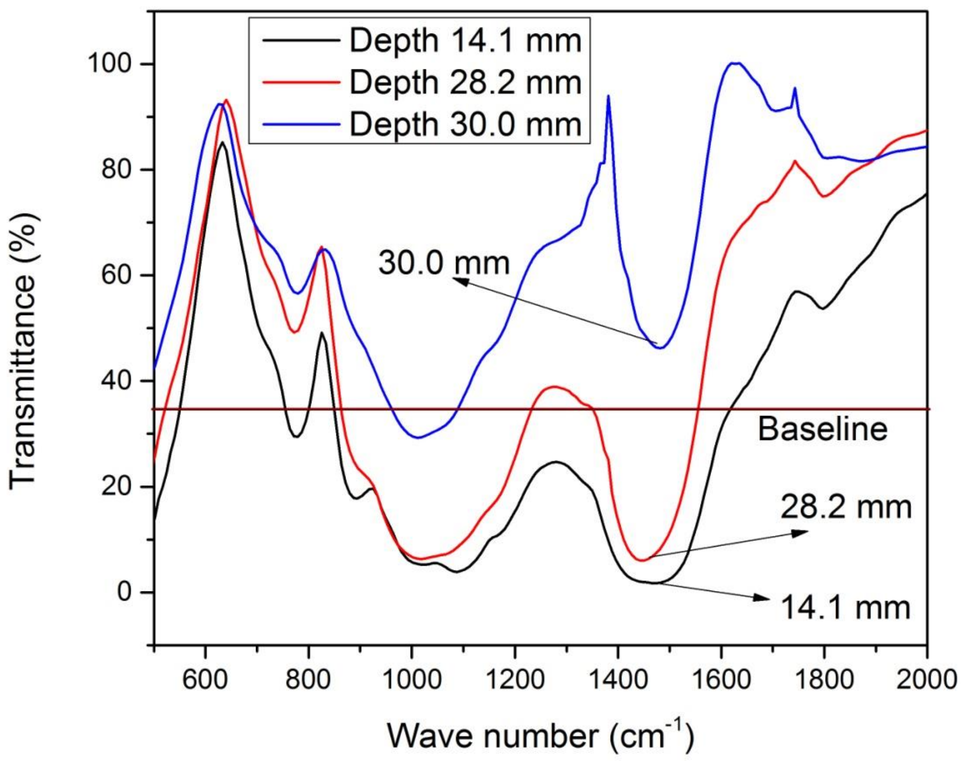


Fig 4.33 FTIR RESULTS FOR PPC CONCRETE AT W/C 0.45

From Figure 4.33 it can be inferred that depth of carbonation in concrete sample of PPC cement with 0.45 W/C is 29.4 mm, since the trough values lying in the range of Wave number 1410-1510 cm^{-1}falls below the base line for each of the graphs pertaining to depths of 14.1 mm and 28.2 mm and lies above the baseline for 30.0 mm. Since the baseline is in between the graphs for 28.2 mm and 30.0 mm, it can be inferred that depth of carbonation is 29.4 mm.

4.5.6 For PPC Concrete with W/C 0.5

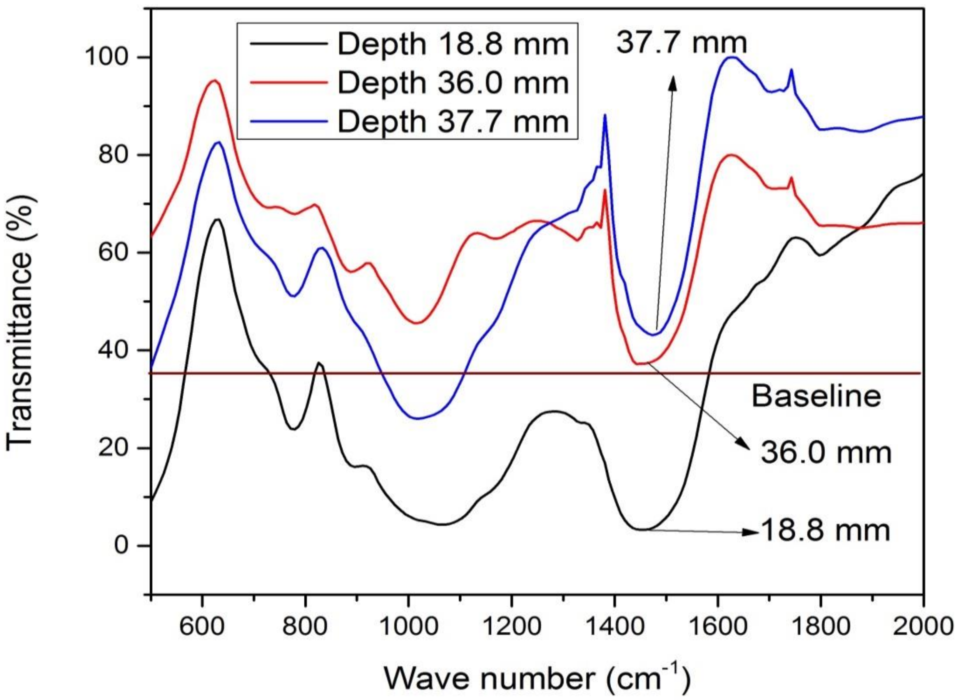


Fig 4.34 FTIR RESULTS FOR PPC CONCRETE AT W/C 0.5

From Figure 4.34 it can be inferred that depth of carbonation in concrete sample of PPC cement with 0.5 W/C is 34.0 mm, since the trough values lying in the range of Wave number 1410-1510 cm^{-1}falls below the base line for the graph pertaining to depths of 18.85 mm and lies above the baseline for each of the graphs pertaining to 36.0 mm and 37.75 mm. Since the graph corresponding to 36.0 mm depth is near the baseline, it can be inferred that depth of carbonation is 34.0 mm.

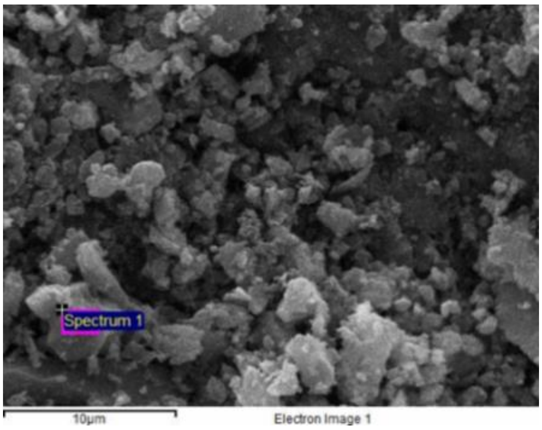
4.6 Results Obtained From SEM-EDX Analysis

SEM-EDX Analysis were done on concrete samples with different W/C at 3 days curing period, 4 % CO_2 concentration, 65 % relative humidity and retention period of 20 days in carbonation chamber for both OPC and PPC concrete. The SEM images and corresponding EDX analysis reflects the presence of products like calcium, oxygen and carbon, owing to the presence of calcite. Since calcite results from carbonation, SEM EDX analysis at different depths of the concrete test sample indicates the depth of carbonation.

Results obtained are as follows:

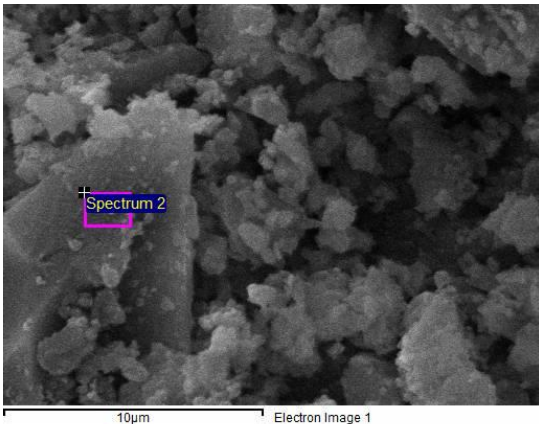
4.6.1 OPC concrete at W/C 0.4

4.6.1(a) Tests results at 8.8 mm



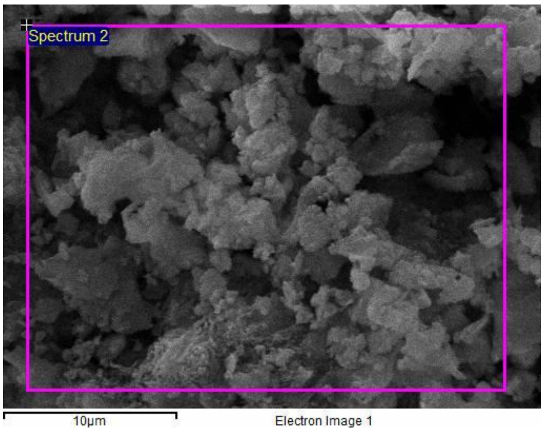
Element	Weight%	Atomic%
C K	23.02	34.12
O K	42.41	47.19
Mg K	8.58	6.28
Si K	4.49	2.85
Ca K	21.51	9.55
Totals	100.00	

4.6.1(b) Tests results at 9.2 mm



Element	Weight%	Atomic%
C K	24.26	35.81
O K	41.00	45.43
Si K	17.96	11.33
Ca K	16.79	7.42
Totals	100.00	

4.6.1(c) Tests results at 11.0 mm

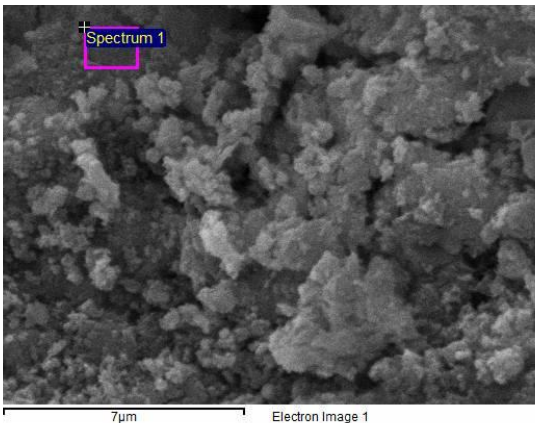


Element	Weight%	Atomic%
O K	55.25	71.95
Al K	3.91	3.02
Si K	17.14	12.72
Ca K	23.69	12.31
Totals	100.00	

Inference : Carbon content as per above images and data is found at 8.8 mm and 9.2 mm depths but not at 11.0 mm and beyond. From the above it can be concluded that carbonation depth for OPC concrete at W/C 0.4 is 9.2 mm since calcium carbonate is found at depth 8.8 mm and 9.2 mm but not at 11.0 mm and beyond.

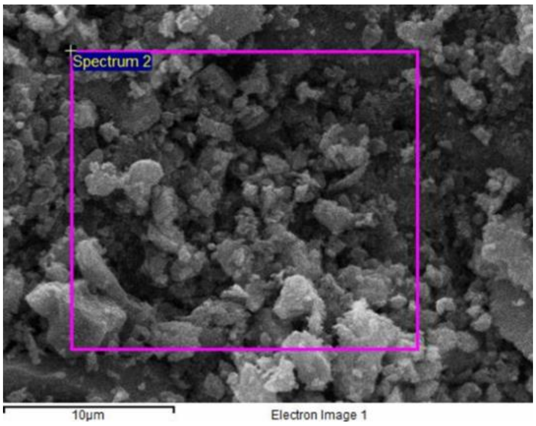
4.6.2 OPC concrete at W/C 0.45

4.6.2 (a) Tests results at 17.0 mm



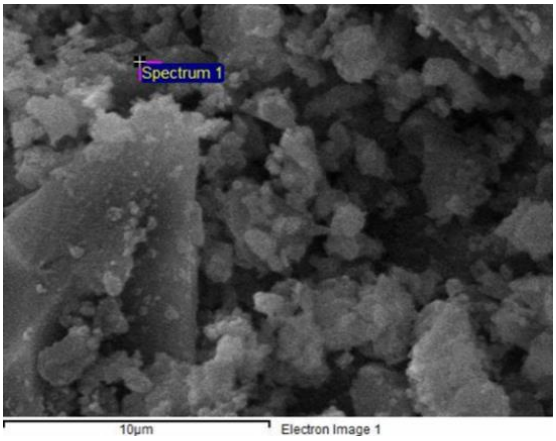
Element	Weight%	Atomic%
O K	50.47	66.78
Al K	10.35	8.12
Si K	19.57	14.75
Ca K	19.61	10.35
Totals	100.00	

4.6.2(b) Tests results at 16.0 mm



Element	Weight%	Atomic%
O K	53.43	71.15
Si K	18.04	13.69
Ca K	28.53	15.16
Totals	100.00	

4.6.2(c) Test results at 14.1 mm

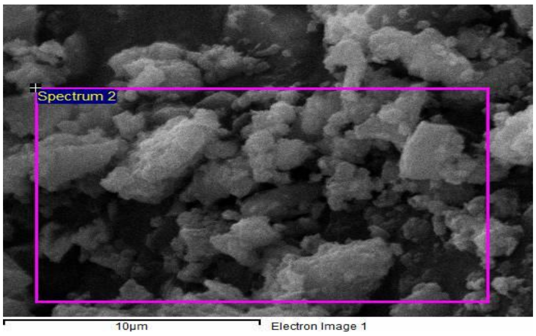


Element	Weight%	Atomic%
C K	36.17	53.11
O K	22.27	24.55
Si K	21.57	13.55
Ca K	19.98	8.79
Totals	100.00	

Inference : Carbon content as per above images and data is found at 14.1 mm depths but not at 16.0 mm and 17.0 mm. From the above it can be concluded that carbonation depth for OPC concrete at W/C 0.45 is 14.1 mm since calcium carbonate is found at depths 14.1 mm but not at 16.0 mm and 17.0 mm.

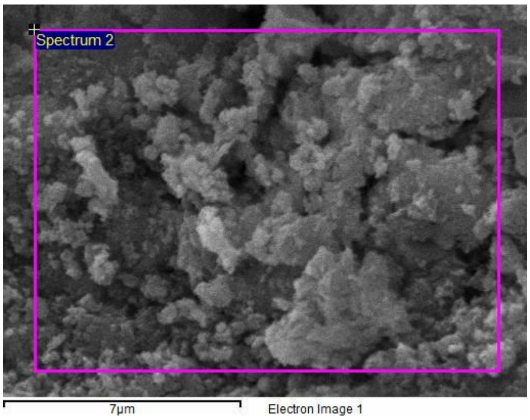
4.6.3 OPC concrete at W/C 0.5

4.6.3(a) Test results at 23.0 mm



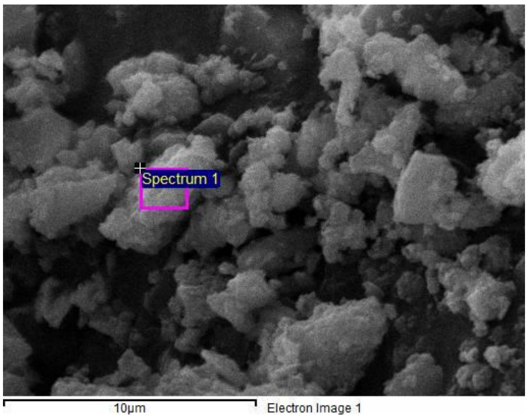
Element	Weight%	Atomic%
O K	65.25	79.05
Mg K	3.58	2.85
Si K	14.67	10.12
Ca K	16.50	7.98
Totals	100.00	

4.5.3(b) Test results at 21.0 mm



Element	Weight%	Atomic%
O K	55.22	71.49
Al K	8.02	6.16
Si K	15.24	11.24
Ca K	21.52	11.12
Totals	100.00	

4.5.3(c) Test results at 18.7 mm

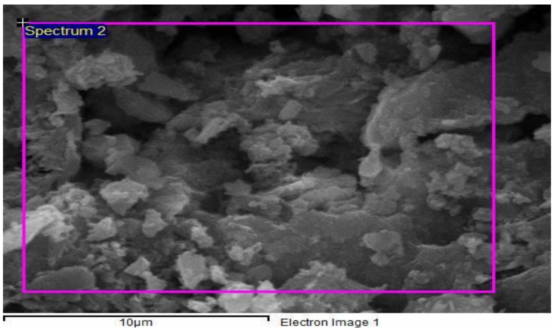


Element	Weight%	Atomic%
C K	40.61	51.29
O K	44.30	42.00
Si K	6.16	3.33
Ca K	8.93	3.38
Totals	100.00	

Inference : Carbon content as per above images and data is found at 18.7 mm depths but not at 21.0 mm and 23.0 mm. From the above it can be concluded that carbonation depth for OPC concrete at W/C 0.5 is 18.7 mm since calcium carbonate is found at depths 18.7 mm but not at 21.0 mm and 23.0 mm.

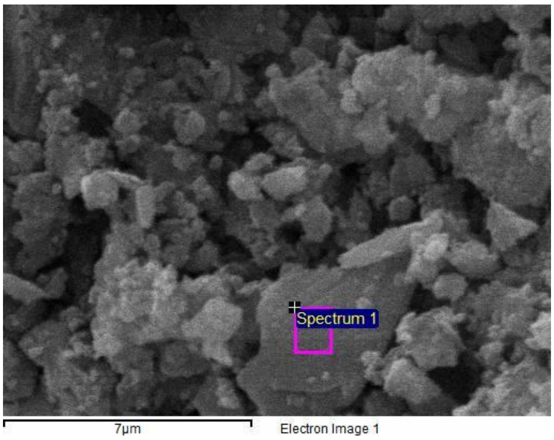
4.6.4 PPC concrete at W/C 0.4

4.6.4(a) Test results at 16.0 mm



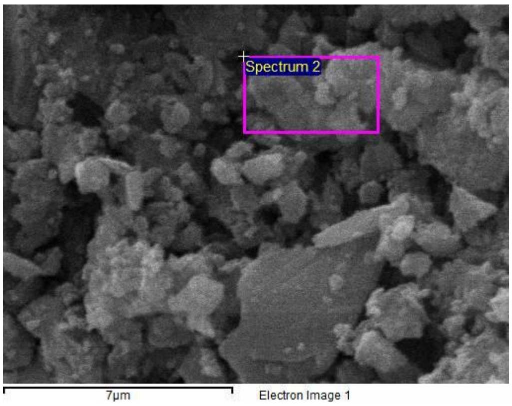
Element	Weight%	Atomic%
O K	57.24	74.78
Al K	1.96	1.52
Si K	10.86	8.08
Ca K	29.93	15.61
Totals	100.00	

4.6.4(b) Test results at 15.0 mm



Element	Weight%	Atomic%
O K	48.94	66.39
Al K	4.04	3.25
Si K	20.83	16.10
K K	6.54	3.63
Ca K	19.64	10.64
Totals	100.00	

4.6.4(c) Test results at 13.1 mm

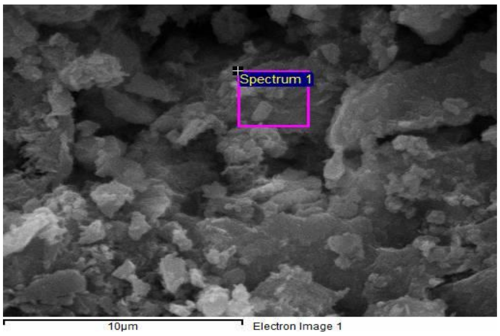


Element	Weight%	Atomic%
C K	21.35	32.62
O K	43.12	49.44
Al K	1.13	0.77
Si K	8.11	5.29
Ca K	25.11	11.49
Fe K	1.19	0.39
Totals	100.00	

Inference : Carbon content as per above images and data is found at 13.1 mm depths but not at 15.0 mm and 16.0 mm. From the above it can be concluded that carbonation depth for PPC concrete at W/C 0.4 is 13.1 mm since calcium carbonate is found at depths 13.1 mm but not at 15.0 mm and 16.0 mm.

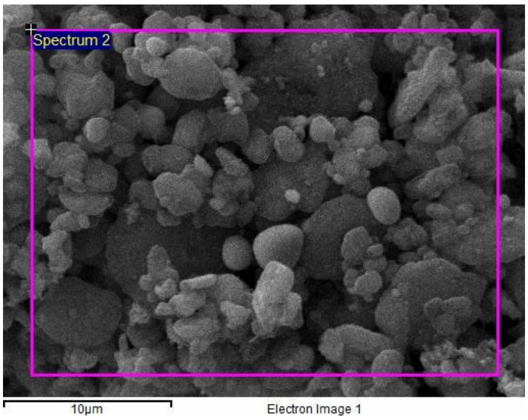
4.6.5 PPC concrete at W/C 0.45

4.6.5 (a) Test results at 30.0 mm



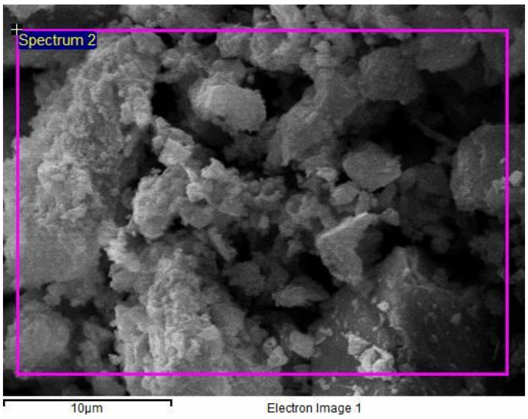
Element	Weight%	Atomic%
O K	44.09	63.74
Al K	5.98	5.13
Si K	9.37	7.71
Ca K	40.56	23.41
Totals	100.00	

4.6.5(b) Test results at 28.0 mm



Element	Weight%	Atomic%
O K	16.36	28.72
Si K	4.21	4.21
S K	69.59	60.96
Ca K	5.81	4.07
Fe K	4.03	2.03
Totals	100.00	

4.6.5(c) Test results at 26.9 mm

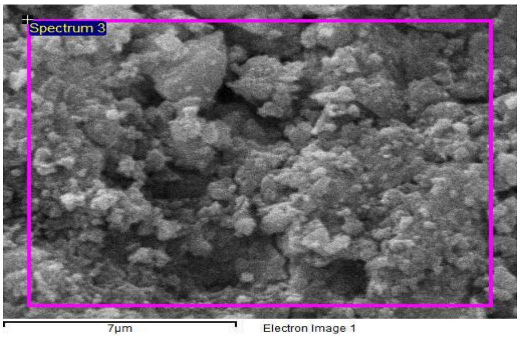


Element	Weight%	Atomic%
C K	24.85	35.92
O K	44.83	48.64
Mg K	1.40	1.00
Al K	1.81	1.16
Si K	9.61	5.94
Ca K	15.55	6.73
Fe K	1.96	0.61
Totals	100.00	

Inference : Carbon content as per above images and data is found at 26.9 mm depths but not at 28.0 mm and 30.0 mm. From the above it can be concluded that carbonation depth for PPC concrete at W/C 0.45 is 26.9 mm since calcium carbonate is found at depths 26.9 mm but not at 28.0 mm and 30.0 mm.

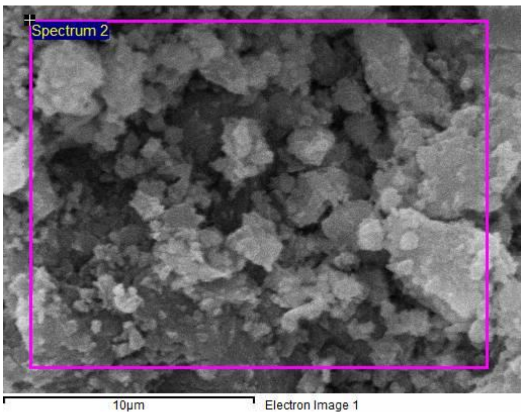
4.6.6 PPC concrete atW/C 0.5

4.6.6(a) Test results at 40.0 mm



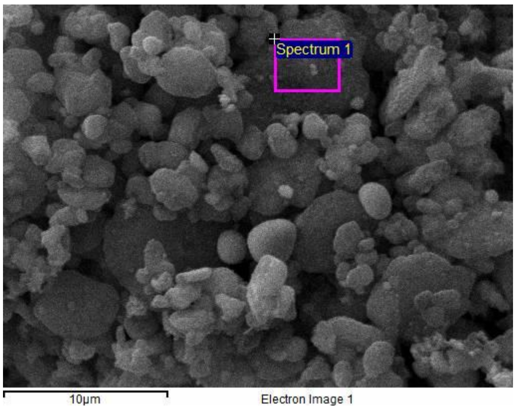
Element	Weight%	Atomic%
O K	42.54	62.70
Mg K	1.85	1.79
Si K	19.14	16.07
K K	1.98	1.19
Ca K	27.49	16.17
Br L	7.01	2.07
Totals	100.00	

4.6.6(b) Test results at 38.0 mm



Element	Weight%	Atomic%
O K	48.41	66.08
Mg K	2.43	2.18
Al K	4.82	3.91
Si K	15.76	12.25
Ca K	28.59	15.58
Totals	100.00	

4.6.6(c) Test results at 36.7 mm



Element	Weight%	Atomic%
C K	40.23	64.31
O K	0.23	0.28
Si K	0.58	0.40
S K	57.05	34.16
Ca K	1.41	0.68
Fe K	0.49	0.17
Totals	100.00	

Inference : Carbon content as per above images and data is found at 36.7 mm depths but not at 38.0 mm and 40.0 mm. From the above it can be concluded that carbonation depth for PPC concrete at W/C 0.5 is 36.7 mm since calcium carbonate is found at depths 36.7 mm but not at 38.0 mm and 40.0 mm.

4.7 Comparison of Carbonation Depth Obtained From Various Methods

4.7.1 Comprasion of carbonation depth of OPC Concrete obtained from Phenolphthalein, XRD, SEM EDX and FTIR nethod are, given in table 4.23 and shown plotted in Figure 4.35

Table 4.23 - Comparison of Carbonation of OPC Concrete Obtained using various methods

Mix	W/C	Carbonation Depth (mm)			
		Phenolphthalein	XRD	SEM EDX	FTIR
O_1	**0.4**	4.4	8.8	9.2	9.4
O_2	**0.45**	7.5	15.2	14.1	15.3
O_3	**0.5**	10.1	19.4	18.7	19.7

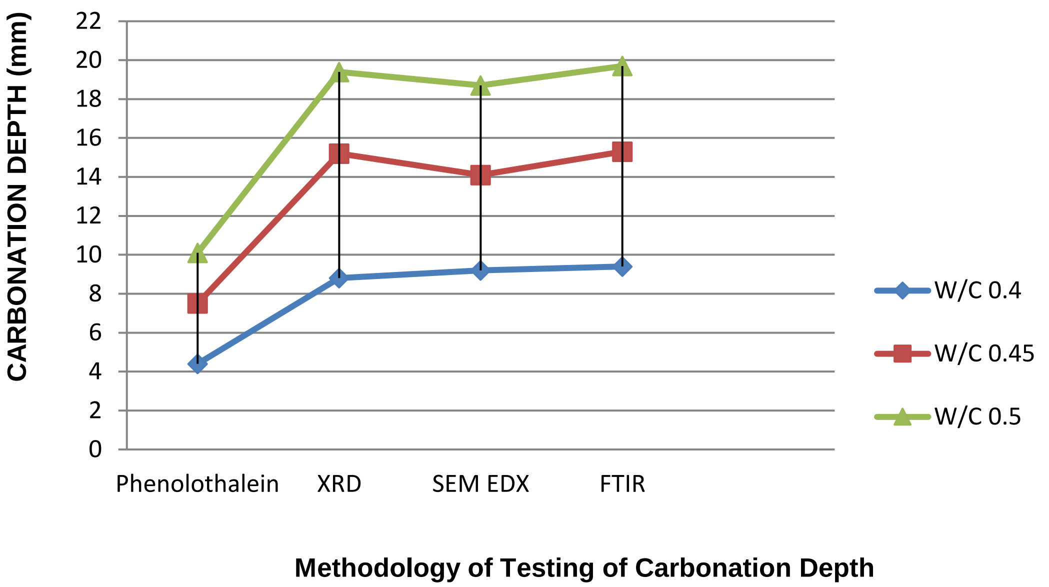


FIG.4.35 - Comprasion of Carbonation Depth of OPC Concrete by Various Methods

4.7.2 Comprasion of Carbonation Depth of PPC Concrete obtained from Phenolphthalein, XRD, SEM EDX and FTIR Method are, given in table 4.24 and plotted in Figure 4.36.

Table 4.24 - Comparison of Carbonation Depth of PPC Concrete by Various Methods

Mix	**W/C**	**Carbonation Depth (mm)**			
		Phenolphthalein	**XRD**	**SEM EDX**	**FTIR**
P_1	**0.4**	8.2	14	13.1	16.3
P_2	**0.45**	14.1	28.2	26.9	29.4
P_3	**0.5**	18.85	38.9	36.7	34

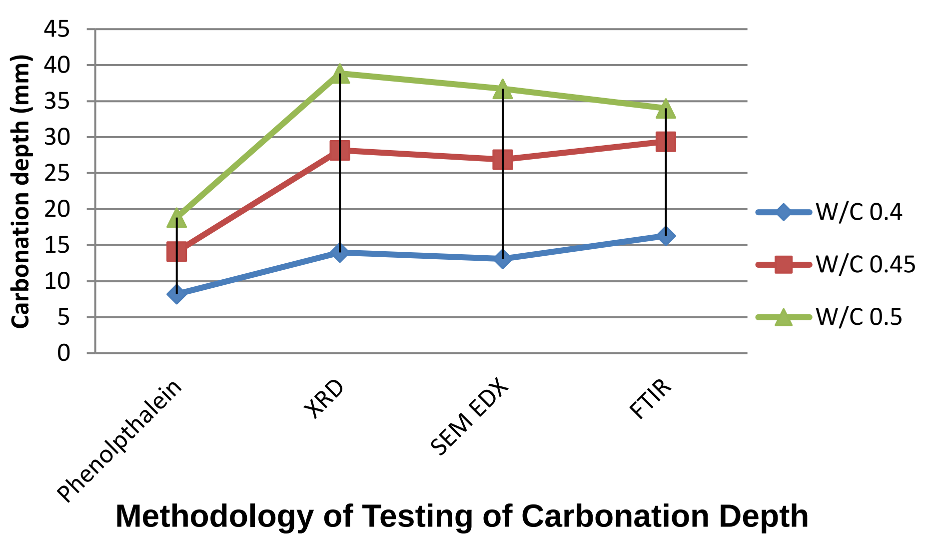


Fig 4.36 Comparison of Carbonation Depth of PPC Concrete by Various Methods

From the above figures it can be inferred that the carbonation depth obtained from advance methods are much higher than those obtained from conventional phenolphthalein indicator method, while the results obtained from different advanced methods i.e. XRD, FTIR and SEM are nearly comparable.

4.8 Comparison of Carbonation Depth of OPC Conrete and PPC Concrete

4 % CO_2 and 65 % Relative Humidity

Carbonation Depths of OPC Conrete and PPC Concrete at 4 % CO_2 and 65 % Relative Humidity for variable periods of exposure are given in table 4.25

Table 4.25 Carbonation Depth of OPC Concrete vs. PPC Concrete

	Mix	W/C	Carbonation Depth (mm)			
			Period of Exposure (days)			
			3	7	21	28
OPC	O_1	0.4	4.4	4.1	4	3.9
	O_2	0.45	7.5	6.9	6.7	6.5
	O_3	0.5	10.1	9.1	8.8	8.5
PPC	P_1	0.4	8.25	7.45	7.35	7.15
	P_2	0.45	14.1	12.77	12.15	11.88

P_3	0.5	18.85	16.84	16.25	15.85

From the above table, it can be clearly seen that carbonation depth for PPC concrete are much higher than those in OPC concrete.

4.9 Conclusions

The following can be concluded from the above results

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

b. The use of superplasticizers 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 must be ensured.

d. Replacement of fine aggregate with fly ash/GGBS is recommended for both OPC and PPC concrete to reduce the effect of carbonation Replacement of cement with fly ash or micro silica up to 10% is recommended for reduction in carbonation only i.e. Replacement of OPC cement with fly ash or micro silica is recommended for reduction in carbonation

e. Replacement of OPC cement with up to 30% of GGBS is recommended for reduction in carbonation.

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

g. Carbonation depth obtained from advance methods are higher than those obtained from conventional phenolphthalein indicator method, while the results obtained from different advanced methods i.e. XRD, FTIR and SEM are nearly comparable.

h. It can be seen that for both OPC and PPC concrete also, carbonation initially increases with an increase in RH up to 85 % and then subsequently decreases with increase of RH

i. Carbonation depth increases with increase in percentage of CO_2 concentration for both OPC and PPC concrete. This indicates that rate of carbonation depends on the rate of diffusion of CO_2 into the concrete sample.