

Shrinkage Reduction in AAC Blocks using Bottom Ash and Silica Sand Replacements

A Focus on Solid Waste Management

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ABSTRACT: Autoclave Aerated Concrete is a widely used construction material all over the world. But, shrinkage cracking over walls constructed using AAC bricks decreased customer interest in Indian market. This study aims to reduce shrinkage and cracking in AAC blocks using adequate filler replacements – bottom ash and silica sand - in compatible proportions. A total of six replacement mix-designs are composed and compared with the reference mix designs. Three mix designs are composed by replacing fillers – fly ash and pond ash – with bottom ash in 25%; and with silica sand in 20% and 50% proportions. The other 3 mix designs are composed by replacing total solids with silica sand in 20%, 25% and 30% proportions. Shrinkages are measured weekly for 91 days using length comparator apparatus. Compressive strength and density of the mix designs are also measured for performance analysis. The result shows that carbonation is the major cause of shrinkage and strength reduction in AAC. Silica sand replacement in larger percentages reduces carbonation shrinkage. Whereas, filler replacement with silica sand in larger percentages increase drying shrinkage. Bottom ash replacements in smaller proportions are not feasible enough to reduce shrinkage in AAC. Bottom ash mix design showed slight increase and silica sand mix designs showed slight decrease in density as compared to the reference mix designs. All replacement mix designs reduced extent of carbonation as compared to reference mix designs.

KEYWORDS: Autoclaved Aerated concrete, Shrinkage of AAC, Microstructure of AAC, Carbonation of AAC, Drying shrinkage.

1. INTRODUCTION

Autoclaved Aerated Concrete (AAC) is a foam concrete building material made using adequate foaming methods and cured using autoclaving method. The major significance of AAC is its low density and light weight structure. Narayanan, N. et. al. (2000) and Ramamurthy, K. et. al. (2009) describes that the low density structure of AAC is achieved by inclusion of air voids of size 1 – 3 mm. Thus, the AAC blocks simultaneously provide structure, heat insulation, fire resistance and excellent acoustical insulation.

In the present Indian scenario, cracking are found on the finished masonry walls constructed using AAC blocks a few weeks or months after the construction. These cracks are mainly seen on Hot-dry regions and summer seasons. Studies by Matsushita, F. et. al. (2004) show that carbonation is one of the major reasons for shrinkage in AAC blocks. Thus, hypothesis is made that higher reactive binders is the reason for this carbonation and addition of less reactive binders would help to reduce the carbonation shrinkages. Thus, this Project aims to reduce these cracks by reduction of shrinkages using partial replacement of existing binders with less reactive ones.

In this study, two AAC manufacturing companies are giving assistance on lab test for workability and manufacturing of the samples. More emphasis of this study is given for reduction of shrinkage since it is found to be the reason for cracking in AAC blocks. Filler replacement in adequate proportions is the methods chosen for shrinkage reduction. Kurama,

H. et. al. (2009) and Wongkeo, W. et. al. (2010) previously studied the compatibility of Bottom ash and silica fume as AAC replacements. Thus, Bottom ash and Silica sand are used as filler replacements. Mix-designs with filler replacements are made by modifying the reference mix-designs currently used by both manufacturers and no new mix designs are introduced to avoid impediments which may happen in the industrial scale production. Also, the project aims only to reduce shrinkage, giving no special prominence on strength modifications. Compressive strength and density are checked only as a measure of performance for industrial scale production. The late availability of one mix-design specimens restricted its study to 63 days only

2. MATERIALS AND EXPERIMENTAL

2.1. Materials

AAC companies generally use binders as Cement, Lime and Gypsum; and fillers as Flyash and Pond ash. During this study, two new replacements are introduced – Bottom ash and Silica sand. Even though Quartz sand with high silica content is the commonly used filler in many countries, AAC companies in India doesn't use it mainly because of its high price.

2.1.1. Bottom ash

Bottom ash for this study is procured from Indira Gandhi Super Thermal Power Project (IGSTPP), Jharli village, Jhajjar district, Haryana. Water to Solid (W/S) ratio is modified based on desired flowability of the filler slurry.

2.1.2. Silica sand

Finest grade of silica sand is chosen for better results. Silica sand for this study is procured from NECC mining corporation, Charkhi Dadri, Bhiwani district, Haryana. Since silica sand has high density as compared to flyash and pond ash, rise has to be achieved same as that of reference mix with varying W/S ratio.

2.2 Mix designs and Specimens

The typical compositions used by both manufacturers in percentage by weight are as shown in Table 1.

Table 1: Mix-designs of AAC used by Manufacturer I and Manufacturer II in percentage by weight. (Source: Author)

Sl.No.	Material	Manufacturer I	Manufacturer II
1	Cement (OPC 53)	21.80 %	11.50 %
2	Lime	7.50 %	8.45 %
3	Flyash	45.50 %	79.00 %
4	Pond ash	23.70 %	
5	Gypsum	1.40 %	1.00 %
6	Aluminium powder	0.10 %	0.05 %

Manufacturer I use pre-defined percentage for flyash and pond-ash in the filler slurry. Manufacturer II use the combined filler slurry percentage to reach 79% of total solid content in which, composition of flyash and pond-ash percentage varies based on their quality and adsorbed water content to get desired slurry flow. In industrial production, it has to be decided based on the flow of filler slurry.

Basic variation in these compositions is the change in cement content. Manufacturer I use approximately double the amount of cement used by Manufacturer II on their mix-design. This results in increase in aluminium necessity also. Aluminium content varies between 0.085% – 0.1% for Manufacturer I whereas, it varies in between 0.45% - 0.54% for Manufacturer

II. Gypsum is not taken into account during TSC replacement due to its smaller content. Manufacturer I uses W/S = 45% and Manufacturer II uses a W/S = 44%. These W/S ratios have to be improved for filler replacements to achieve same flowability and density. Aluminium content is kept constant for reference.

Various mix designs and their proportions to be carried out during this study are as shown in Table 2.

Table 2: Replacement Mix-designs - SS replacements are done for percentage of TSC in Manufacturer I whereas, SS/BA replacements are done for percentage of slurry solid content (FA + PA) in Manufacturer II (Source: Author)

Material	Percentage by weight					
	Manufacturer I			Manufacturer II		
	20% SS (TSC)	25% SS (TSC)	30% SS (TSC)	25% BA (Slurry)	20% SS (Slurry)	50% SS (TSC)
OPC	17.44	16.35	15.26	11.50	11.50	11.50
Lime	6.00	5.60	5.25	8.45	8.45	8.45
Flyash	36.40	34.10	31.80	59.25	63.20	39.50
Pond ash	18.96	17.75	16.59			
Gypsum	1.40	1.40	1.40	1.00	1.00	1.00
Silica sand	19.70	24.70	29.60	--	15.80	39.50
Bottom ash	--	--	--	19.75	--	--
Aluminium powder	0.10	0.10	0.10	0.05	0.05	0.05

2.3 Workability tests

The objective of workability tests is to find out the desired W/S ratio for all mix-designs. Workability tests are conducted in lab conditions where, mainly flowability, density and strength are tested. Production scale blocks have density varying in between 550 – 600 kg/m³ and compressive strength not less than 4 MPa. Since industrial conditions of temperature and other factors can't be maintained in lab scale, rising and density of specimen made in lab conditions can't be comparable with the production scale blocks. Thus, the method adopted is to compare all the mixes with reference mix composed in lab conditions. All lab testing are done on a scale of weight batching for 1 kilogram. Mixing is done for the same duration used in industrial conditions (180 seconds) using mechanical mixer. Two 70 X 70 X 70 mm cubes are casted for each

mixes for measurement of strength and density. All specimens are autoclaved in industrial scale autoclave so that no variation in properties happens due to it. W/S ratio is adjusted further for each mix to get desired flowability, density and compressive strength.

2.4 Industrial casting

Manufacturer I uses fully computerized discharge of materials into the mixing chamber. Whereas, Manufacturer II first prepares the filler slurry and checks it for desired density and flowability; the slurry is then pumped to the computerized mixing machines. Thus, replacement materials are added manually to the chamber in Manufacturer I whereas, replacement are done in the filler slurry in Manufacturer II. Slurry density and flowability in Manufacturer II are adjusted to 1540 – 1560 kg/m³ and 200 ± 10 mm respectively. W/S ratio is adjusted in filler slurry to get these desired values. Moulds in Manufacturer I & II are of sizes 3 m³ and 4.5 m³ respectively. Thus, total dry solid weighs around 1750 – 1800 kg and 2800 – 3000 kg; and, discharge flow weighs around 3000 kg and 4000 kg respectively. Mixing process is fixed as 180 seconds. Discharge wet density ranges between 730 – 770 kg/ m³ to get the final dry density to be 550 – 600 kg/ m³. Discharge flow is measured readily after the discharge and in all conditions to be 150 ± 10 mm. The slurry is filled only 1/3rd of the moulds; and, rise is approximately 2/3rd or 65% of the total mould height.

2.5 Testing and Specimens

2.5.1 Testing conditions

Table 3: Testing conditions (Source: Author)

Sl.no.	Condition	Temperature	Relative humidity	CO ₂ concentration
1	Natural condition	Natural	Natural	Natural
2	Accelerated carbonation	27 °C	65%	3%
3	0% RH	27 °C	0%	Natural
4	100% RH	27 °C	100%	Natural

All specimens are kept in a temperature controlled room to reduce errors due to thermal expansions. Accelerated carbonation is obtained using carbonation test chamber and 0% RH condition by covering the specimens with activated silica gel.

2.5.2 Shrinkage analysis

As specified in IS 6441 – Part II (1972), specimens for shrinkage determination are cut to the size of 40 X 40 X 300 mm (length not less than 150 mm as per standard). Length Comparator Apparatus (as per IS 9459:1980) of

0.01 mm precision is used for measuring the shrinkages. The specimens have to be drilled on both ends with a diameter of 1.5 mm for end pins of length comparator apparatus. These end pins are made up of steel and fitted with the help of epoxy or cement paste. These pins are fixed in the length comparator apparatus to facilitate the observation in the dial gauge. The analogue dial on length comparator has least count of 10 microns.

2.5.3 Compressive strength test

As per IS 6441 – Part V (1972), the specimens for compressive strength testing are of size 150 X 150 X 150 mm. A minimum of three cubes for each mix designs are tested using Compression Testing Machine with a maximum error of ±2.0%.

2.5.4 Unit weight/ Density test

As per IS 6441 – Part I (1972), density tests are done on specimens of size 100 X 100 X 100 mm. Also, the specimens for unit weight calculation are of same batch with the specimens for compressive strength testing, as specified in the IS code.

2.5.5 Carbonation using XRD & phenolphthalein test

Extent of carbonation is tested on cube specimens of size 100 X 100 X 100 mm under natural and accelerated carbonation conditions. During the test, the cubes are broken into halves and phenolphthalein solution is sprayed. Carbonated area doesn't show any colour variation due to its increase in pH level.

X – Ray Diffraction analysis before and after carbonation is used to check the variations in compositions.

3. RESULTS AND ANALYSIS

3.1. Shrinkage analysis

A comparison of maximum strains occurred in all mix-designs during all conditions for 91 days is given in Figure 1 and Table 4.

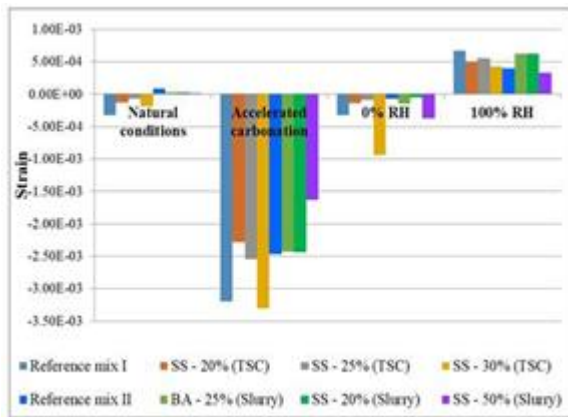


Figure 1: Maximum strain of mix-designs in testing conditions (Source: Author)

Table 4: Maximum strain of mix-designs in testing conditions (Source: Author)

		Natural conditions	Accelerated carbonation	0% RH	100% RH
Manufacturer I	Reference mix I	-3.18E-04	-3.19E-03	-3.23E-04	6.74E-04
	SS - 20% (TSC)	-1.23E-04	-2.28E-03	-1.33E-04	4.98E-04
	SS - 25% (TSC)	-7.23E-05	-2.54E-03	-8.81E-05	5.59E-04
	SS - 30% (TSC)	-1.86E-04	-3.31E-03	-9.37E-04	4.26E-04
	Reference mix II	8.60E-05	-2.47E-03	-6.95E-05	4.01E-04
Manufacturer II	BA - 25% (Slurry)	3.17E-05	-2.43E-03	-1.45E-04	6.22E-04
	SS - 20% (Slurry)	2.61E-05	-2.44E-03	-5.01E-05	6.24E-04
	SS - 50% (Slurry)	1.60E-05*	-1.63E-03*	-3.72E-04*	3.31E-04*

Main observations by comparison of maximum strain occurring in different mix designs are as follows:

- Carbonation is the major cause of shrinkage in AAC blocks. Reference mixes I & II caused 10 and 30 times more shrinkage during carbonation than drying respectively.
- All silica sand replaced mix-designs (with SC) showed significant reduction in shrinkage during natural conditions. A maximum reduction of 78% is attained with 25% silica sand replacement (with TSC) in natural condition.
- 20% Silica sand replacement (with TSC) mix- design attained a maximum of 30% shrinkage reduction during accelerated carbonation condition.
- 50% silica sand replaced mix-design (with filler slurry) attained a maximum reduction of 34% in shrinkage during accelerated carbonation as compared to reference.
- For 25% bottom ash and 20% silica sand replaced mix designs (with filler slurry), Initial shrinkage increased

by a maximum of 98% (by 14 days) and final shrinkage reduced by a maximum of 11% (by 91 days) during accelerated carbonation.

- 20% and 25% silica sand replaced mix-design (with TSC) attained significant reduction in drying shrinkage up to a maximum of 87% during 0% RH condition.
- Silica sand replacement in larger percentages increases the drying shrinkages severely. 30% silica sand replacement with TSC and 50% silica sand replacement with filler slurry content increased the drying shrinkages by approximately 2 times and 5 times as compared to the reference.
- Carbonation and drying are the causes of shrinkage in AAC. Since there is no carbonation and drying at 100% RH conditions, none of the specimens showed any shrinkage during this condition.
- Some specimens with less or no shrinkages showed thermal expansion.

3.2 Compressive strength

A comparison of compressive strength of all specimens after 91 days is given in Figure 2 & Table 5.

Main observations on compressive strength of mix designs in the above mentioned conditions after 91 days are as follows:

- Carbonation reduces the compressive strength of AAC. As comparing natural and accelerated carbonation conditions, a maximum reduction of 57% in compressive strength is observed for Reference mix I.
- The 20% and 25% silica sand replacement mix-designs (with TSC) showed 42% and 29% reduction in compressive strength respectively. Reduction in binder content is the main cause of this reduction.
- 20% and 25% silica sand replacement mix-designs (with TSC) showed comparatively higher compressive strength with respect to the reference during accelerated carbonation condition. Reduction in carbonation is the reason for this less reduction in strength.

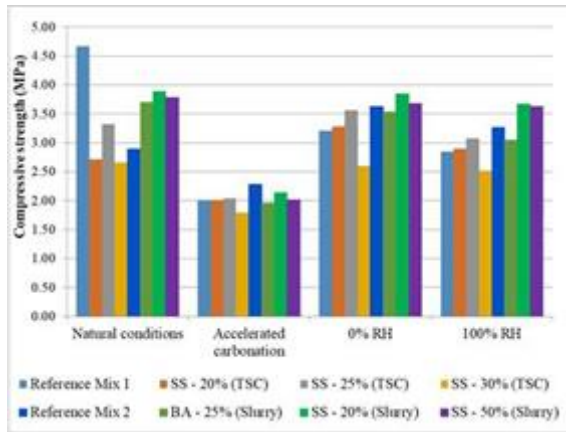


Figure 2: Compressive strength of all mix-designs after 91 days in testing conditions (Source: Author)

Table 5: Compressive strength of all mix-designs after 91 days in testing conditions (Source: Author)

		Natural condition	Accelerated carbonation	0% RH	100% RH
Manufacturer I	Reference mix I	-93.69	-110.41	-84.92	-75.02
	SS - 20% (TSC)	-90.24	-54.74	-93.62	-92.06
	SS - 25% (TSC)	-79.45	-41.00	-66.08	-84.97
	SS - 30% (TSC)	-79.15	-32.02	-81.12	-78.61
Manufacturer II	Reference mix II	-101.21	-73.05	-84.16	-29.15
	BA - 25% (Slurry)	-97.48	-85.28	-83.94	-34.76
	SS - 20% (Slurry)	-102.76	-64.66	-87.13	-19.52
	SS - 50% (Slurry)	-68.26*	-51.87*	-65.07*	-9.62*

- The 30% silica sand replacement mix-design (with TSC) showed more reduction in compressive strength as compared to reference during all conditions. Major reduction in binder contents is the reason for severe reduction in compressive strength.
- All replacement mix-designs (with filler slurry) showed less reduction in compressive strength as compared to the Reference mix-design II during natural condition. Whereas, they showed more reduction during accelerated carbonation condition.
- All replacement mix designs (with filler slurry) showed compressive strength in comparable limits with respect to Reference mix design II in 0% and 100% RH conditions.

3.3 Density

- A comparison of maximum change in density occurred in all mix designs during all conditions after 91 days are given in Figure 3 and Table 6.
- Main observations by comparison of maximum

change in density occurring in different mix-designs are as follows:

- All replacement mix-designs showed approximately same reduction in density with respect to references during natural condition. Major change is observed only for 50% silica sand replacement mix-design.
- All replacement mix-designs (with TSC) showed very less change in density as compared to the references during accelerated carbonation.

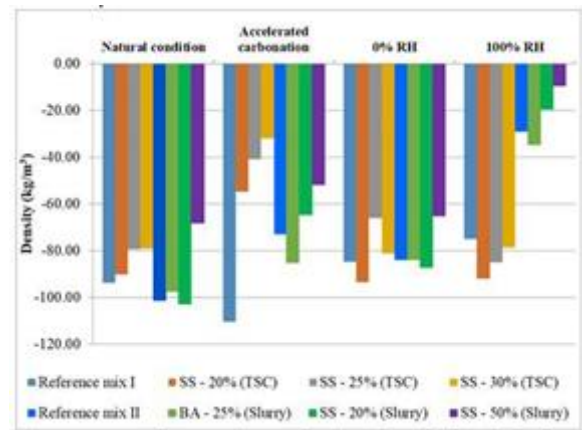


Figure 3: Maximum change in density of all mix-designs after 91 days in various conditions (Source: Author)

Table 6: Maximum change in density of all mix-designs after 91 days in various conditions (Source: Author)

		Natural condition	Accelerated carbonation	0% RH	100% RH
Manufacturer I	Reference mix I	-93.69	-110.41	-84.92	-75.02
	SS - 20% (TSC)	-90.24	-54.74	-93.62	-92.06
	SS - 25% (TSC)	-79.45	-41.00	-66.08	-84.97
	SS - 30% (TSC)	-79.15	-32.02	-81.12	-78.61
Manufacturer II	Reference mix II	-101.21	-73.05	-84.16	-29.15
	BA - 25% (Slurry)	-97.48	-85.28	-83.94	-34.76
	SS - 20% (Slurry)	-102.76	-64.66	-87.13	-19.52
	SS - 50% (Slurry)	-68.26*	-51.87*	-65.07*	-9.62*

- Drying doesn't cause major change in density. Also, all replacement mix-designs showed

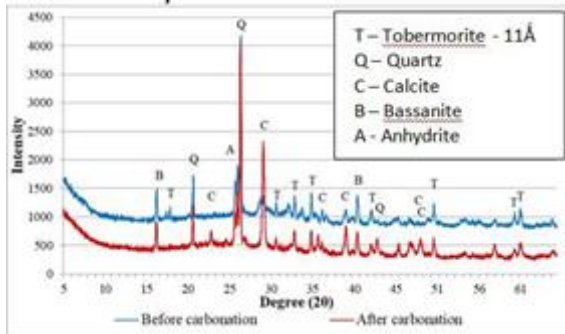


Figure 4: X - Ray Diffraction analysis of AAC before and after carbonation (Source: Author)

core of AAC specimen and

(ii) 91 days accelerated carbonated AAC specimen. Reduction of Tobermorite crystals (180, 310, 330, 430, 500 and 600) and increase in crystalline phase of calcite (230, 290, 360, 390, 480 and 490) is observed in the analysis of XRD. This analysis emphasizes the observations by Kus, H. et. al. (2003) on natural and artificial weathering of AAC; and studies Matsushita, F. et. al. (2004) on carbonation of AAC. Other crystalline phases like Quartz (260), Bassanite and Anhydrite are also present in AAC, whereas, none of them affects any major variations during carbonation.

3.4.2 Phenolphthalein test

All replacement mix-designs showed reduction in extent of carbonation as compared to the references. Maximum reduction of carbonation is attained in 50% slurry solid replaced by silica sand mix-design. This mix-design affected approximately 50% carbonation during 91 days. Carbonation study shows that addition of less reactive fillers - bottom ash and silica sand - can reduce extend of carbonation in AAC. Increasing

(Source: Author)

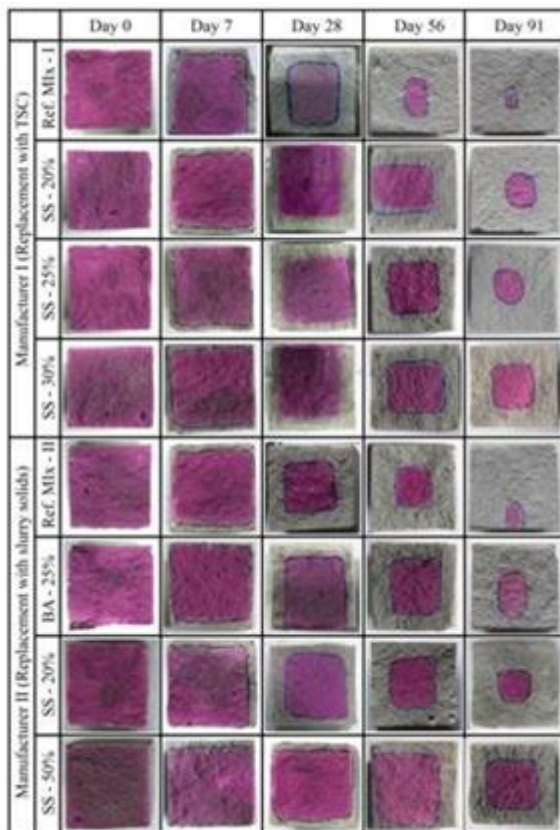


Figure 5: Extent of Carbonation during natural condition approximately same reduction in density as compared to the references.

3.4 Extent of Carbonation

3.4.1 XRD analysis

The reaction during carbonation of AAC can be validated using X - Ray diffraction analysis of samples before and after carbonation. The specimens used here are (i) non-carbonated

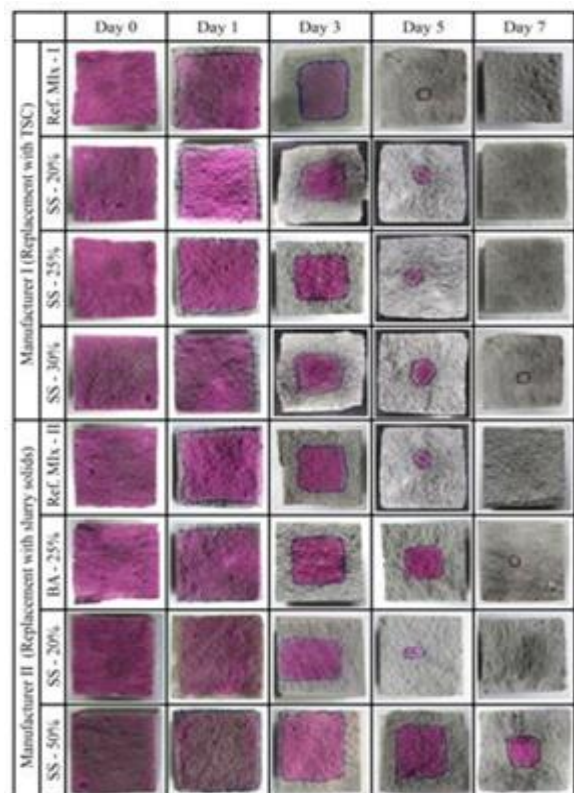


Figure 6: Extent of Carbonation during accelerated carbonation condition (Source: Author)

these filler contents further reduces carbonation. The results are more significant in accelerated carbonation condition. Extent of carbonation of all mix designs under natural and accelerated carbonation condition are shown in Figure 5 and Figure 6.

4. CONCLUSIONS

4.1. Shrinkage

- Carbonation is the major cause of shrinkage in Autoclaved Aerated Concrete. Shrinkage during accelerated carbonation condition is observed 10 times as in natural condition.
- Drying shrinkage is very less as compared to carbonation shrinkage. Shrinkage during accelerated carbonation condition is observed 10 times as in drying condition.
- Silica sand replacements in larger percentage can reduce carbonation shrinkage. On the other hand, it shows significant increase in drying shrinkage.
- Bottom ash replacements in smaller proportions are not feasible enough to reduce shrinkages in AAC.
- Thermal expansion causes error in the calculation of shrinkage. Thus, all specimens for shrinkage study have to be kept at temperature controlled atmosphere before the measurements.

4.2. Compressive Strength

- Carbonation is the major cause of reduction of compressive strength in AAC blocks.
- Filler replacements with Total Solid Content (TSC) reduce binder content; and thus cause reduction in initial compressive strength as compared to the reference mix designs.
- Replacement mix designs affect less reduction in compressive strength with time during all conditions as compared to the reference mix designs.
- Bottom ash and silica sand replaced mix-designs attain comparable or more compressive strength than the reference mix-design by time. Also, silica sand replaced mix-designs attain more strength than the reference mix-designs during

higher relative humidity.

4.3. Density

- AAC blocks attains approximately 15% reduction in density by 3 months after manufacturing
- Water - to - Solids ratio and aluminium content are as important as the constituent materials in density of AAC.
- Bottom ash replaced mix designs causes slightly more reduction in density as compared to the reference mix design.
- Silica sand replacement with TSC causes slightly more reduction in density; whereas, reduction in density of silica sand replaced mix-designs with filler slurry are less than that of reference mix- design.

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