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Original Article

Strength analysis of concrete pavement deformation due to Alkali Silica Reaction (ASR)

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ABSTRACT

Alkali Silica Reaction (ASR) is a chemical reaction that negatively affects concrete pavements strengths and integrity. ASR impedes concrete pavements' performance due to the formation of cracks and ultimate deformation if not properly controlled. Concrete pavements are gaining more relevance due to their ability to be constructed on soils with low bearing capacity and support high traffic loadings, thus increasing the need for studies on how ASR in the concrete pavements can be mitigated. This study employed compressive and flexural strength tests to determine the strength properties and deformation of concrete pavements due to ASR when partially replaced with CBA at varying percentages. Static structural modelling of the concrete as a multiphase material in which aggregates, cracks and gel formations are considered as embedded inclusions in the cement paste is then carried out. The results are then compared with relevant standards and findings of other researchers. The study's findings reveal that all the concrete cube samples passed the recommended compressive strength for rigid pavement, which range from 35 - 40 N/mm^2 at 28th day. The concrete cube samples also passed the target strength of 48.25 N/mm^2 obtained from the mix design. The effect of ASR resulted in lower compressive and flexural strengths observed at 180th and 240th days with lower CBA addition, while samples containing higher CBA contents had increasing compressive strength. The static structural modelling results reveal that the maximum deformation was obtained for the concrete cubes admixed with 0% CBA with 47.045 mm while the least deformation was obtained at 30% CBA replacement with deformation value of 5.542 mm on application of a 900 KN force. Therefore, the study posits that CBA addition will help reduce Portland Cement Concrete Pavement deformation due to ASR in relation to traffic loadings.

1. Introduction

Concrete pavements are becoming increasingly acceptable due to their durability, performance, and lifecycle costs compared to asphaltic pavements. Concrete pavements rigidity, high modulus of elasticity and ability to distribute the load over a relatively wide area of soil makes them a good option for road construction in areas of high traffic density, poor subgrade soils and where funds for maintenance are not readily available as applicable to many developing countries such as Nigeria. Regardless of the several benefits of concrete pavements, they suffer from Alkali Silica Reaction (ASR), which undermines their durability and performance. ASR induces degradation of concrete pavements due to the reaction that occurs between the cement paste and reactive siliceous aggregates, which causes significant expansion depending on the materials used for the construction and exposure conditions of the structure [1].

Similar study by [2] using the finite-element method assessed the mechanical behaviour of damaged structures. The study considered concrete creep, stress induced by the formation of Alkali-Aggregate Reaction (AAR) gel and mechanical damage. [3] studied the residual strength of structural members affected by ASR and examined under a microscope aggregate expansion features consistent with ASR damage. Sustained and cyclic flexural load and longitudinal reinforcement were shown to have significant restraining effects on ASR expansion. Material tests showed that ASR reduced the compressive stiffness,

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resonant frequency and flexural strength of the concrete, but not the compressive strength. [4] undertook a long term alkali activity simulation and showed that replacement of artificial sandstone sand with artificial marble sand reduced the alkali activity expansion rate of the sandstone aggregate and effectively improved the inhibition effect of the aggregate when mixed with 35 % fly ash. This indicates that under their simulation, the strength and durability properties of concrete structures are improved using fly ash.

The production of cement releases Carbon dioxide (CO_2) into the atmosphere as a result of de-carbonation of limestone in the kiln during manufacture of cement and the combustion of fossil fuel. The CO_2 from cement production contributes to greenhouse gas emission, which is estimated to be about 1.35 billion tonnes annually or about 7% of the total gas emissions in the earth's atmosphere [5]. Alternative materials such as Cow Bone Ash (CBA) is therefore researched to access its impact in mitigating the menace of greenhouse gas emission that results from cement production in Portland cement concrete pavement design and construction. In Nigeria, cow bones are readily available as wastes in large quantities. Bones generally take time to decay, which could be millions of years and, if not properly disposed off, defaces the environment. Bones have been confirmed as pozzolanic in nature [6], thereby making it fit for use in Alkali-Silica Reaction studies. Bones are also known not to disintegrate easily, unlike other pozzolanic materials with cases such as bones from Goliaths skull, which is estimated to be between 2900 and 3000 years old still very much in rigid state [7], thereby justifying its use in this study.

Hence the need for studies on strength analysis of concrete pavements deformation affected by Alkali Silica Reaction (ASR) by using cow bone ash. Although, not many research works have been done on this subject, researchers have indicated that ASR's effect could be mitigated by the addition or substitution of finely reactive materials, such as pozzolans, with Portland cement; hence the need for this study.

2. Materials and Methods

The tests conducted on the materials (cement, sand, coarse aggregate and cow bone ash) include determining their physical and chemical properties in their natural state. The proportioning of the concrete components was done according to Road Note 4 methodology. This was followed by the tests conducted on the control samples of the concrete. The concrete is then modified with partial replacement of cement with 0%-30% cow bone ash. Bulk density and compressive strength tests were conducted on the samples at different curing ages (7^{th}, 28^{th}, 56^{th}, 90^{th}, 120^{th}, 180^{th} and 240^{th} days), flexural strength test (7^{th}, 28^{th}, 56^{th}, 90^{th} and 120^{th} days) carried out on the concrete samples.

The compressive strength of concrete is a measure of the concrete's ability to resist loads (traffic loads), which tend to compress it. The compressive strength results are primarily used to ensure that the concrete mixture produced on site meets the requirements of the specified strength (fc') of 40 N/mm^2 in the job specification. The compressive strength was determined on the concrete cubes by the application of the compression load of 3.0 KN/s in accordance with BS 1881: Part 111 (1983). The weight (kg), density (kg/m^3), crushing load (KN) were obtained, which were then used in computing the compressive strength (N/mm^2) of the concrete samples. The weight of each concrete cubes was obtained prior to testing to ascertain the density. This was done in accordance with BS 1881: Part 116 [8].

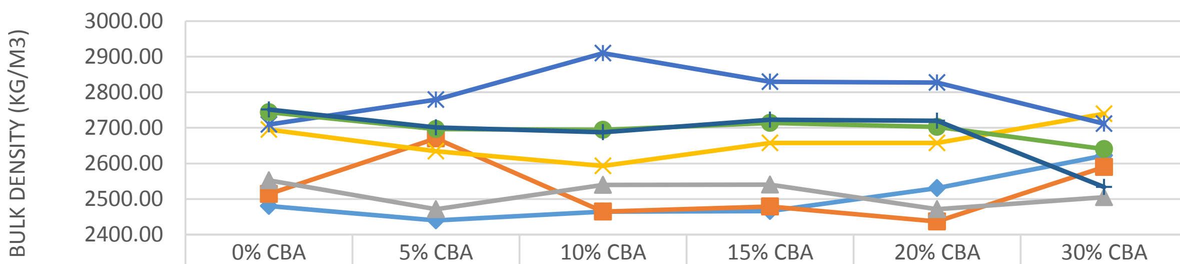
Flexural test evaluates the tensile strength of concrete indirectly. It tests the ability of unreinforced concrete beam or slab to withstand failure in bending as a result of traffic loading (Three Point Load Method – ASTM C78) [9]. It is significant as it helps in Specifying compliance with standards, it is an essential requirement for concrete mix design and it is employed in testing concrete for slab and pavement construction. Flexural strength test of concrete comes to play when a road slab with inadequate sub-grade support is subjected to wheel loads and/or there are volume changes due to temperature/shrinking.

Static structural modeling of the Portland cement concrete pavements with varying CBA percentages was carried out on Parametric Technology Corporation (PTC) Creo. The modeled concrete cubes were then migrated to ANSYS 19.2 using static structural to simulate the effect of the addition of CBA on the concrete when the damaging effect of ASR begins using values obtained from the experimental study at 180^{th} and 240^{th} days. With boundary conditions and constraints determined, a force of 900 KN was applied to the concrete cube in the negative Y direction with the base of the support taken as fixed supports. The total deformation on impact of the force on the concrete cubes was then determined and modelled.

3. Results and Discussion

3.1. Bulk Density

The bulk density, which is a reflection of the concretes ability to function for structural support, water and solute movement, and durability, was carried out in this study. The bulk density is obtained by dividing the weight of the concrete by its total volume. Figure 1 shows the bulk density results for the concrete samples.

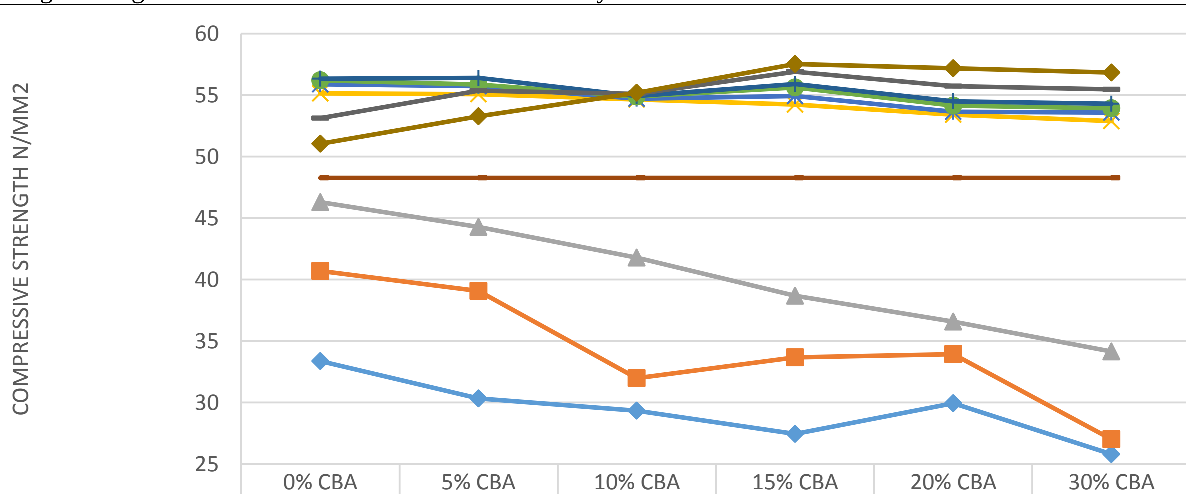


	0% CBA	5% CBA	10% CBA	15% CBA	20% CBA	30% CBA
7th Day	2480.00	2440.00	2464.89	2465.79	2530.37	2622.20
14th Day	2514.05	2669.90	2464.89	2478.82	2437.01	2589.77
21st Day	2552.55	2471.11	2539.26	2540.75	2471.11	2505.15
28th Day	2694.85	2634.05	2592.59	2657.78	2657.78	2739.22
56th Day	2709.59	2779.26	2909.63	2829.63	2826.67	2711.40
90th Day	2743.71	2696.30	2694.32	2714.07	2702.22	2640.00
120th Day	2751.11	2700.74	2687.41	2722.96	2720.00	2533.33

Fig 1. Graph of Bulk Density of Concrete Cubes (Kg/m^3) at different curing ages

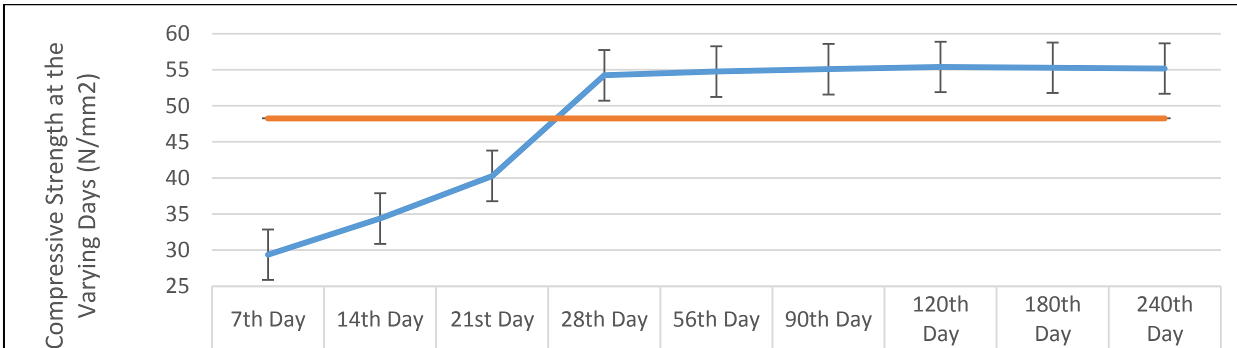
3.2. Compressive Strength

Compressive strength test results obtained for the concrete cube samples are as shown in Figure 2. According to Department of Scientific and Industrial Research for Road Research, London, the study's findings show that all the concrete cube samples passed recommended compressive strength for rigid pavement, which varies from 35 - 40 N/mm^2 at 28th day. The concrete cube samples also passed the target strength of 48.25 N/mm^2 obtained from the study mix design. The concrete cubes at 0% CBA replacement had a compressive strength of 56.32 N/mm^2 while the sample at 30% CBA replacement had a compressive strength value of 53.99 N/mm^2 at the 120th day. The average compressive strengths are also seen to be increasing from the 28th day for all the mix proportions, exceeding the target strength, thereby showing the durability of the concrete cubes, which also indicates their increasing ability to resist ASR. Figures 2 and 3 show the compressive strength results for the concrete samples.



	0% CBA	5% CBA	10% CBA	15% CBA	20% CBA	30% CBA
7th Day	33.35	30.33	29.32	27.43	29.92	25.79
14th Day	40.69	39.07	31.96	33.65	33.92	27.01
21st Day	46.28	44.27	41.78	38.67	36.56	34.14
28th Day	55.14	55.06	54.64	54.23	53.4	52.87
56th Day	55.87	55.71	54.7	54.92	53.63	53.58
90th Day	56.19	55.84	54.86	55.61	54.14	53.92
120th Day	56.32	56.38	54.91	55.88	54.47	54.29
180th Day	53.12	55.34	55.08	56.89	55.72	55.45
240th Day	51.03	53.27	55.18	57.51	57.17	56.82
Target Strength	48.25	48.25	48.25	48.25	48.25	48.25

Fig 2. Variation of Compressive Strength of Cubes (N/mm^2) at different Percentages of CBA and Curing Ages



	7th Day	14th Day	21st Day	28th Day	56th Day	90th Day	120th Day	180th Day	240th Day
Obtained	29.36	34.38	40.28	54.22	54.74	55.07	55.38	55.27	55.16
Target	48.25	48.25	48.25	48.25	48.25	48.25	48.25	48.25	48.25

Fig 3. Variation of Average Compressive Strengths of Cubes (N/mm^2) at Varying Curing Age (Days)

The results show that higher strength is achieved with minimal replacement of cement with CBA. This is also evident in the fact that all values of compressive strength obtained for varying replacements of cement with CBA was lower than that obtained with 100% cement. However, increase in compressive strength of concrete is associated with reduction in alkali silica reaction [10, 11], but the partial replacement of cement with CBA, provided the concrete's target strength, will result in the optimal reduction of ASR in concrete pavements.

Results from [12] showed that at 7th day, concrete maximum compressive strength (31.11 N/mm^2) was exhibited when cement was replaced with 10% silica fume by weight, while at 28th day, the concrete maximum compressive strength (45.33 N/mm^2) was obtained when cement was replaced with 10% silica fume by weight. [13] obtained optimum compressive strength values of 26.25 N/mm^2 on replacing cement with 10% wood waste ash at 7th day while at 28th day, an optimum compressive strength value of 29.74 N/mm^2 was obtained at 10% replacement of cement with wood waste ash. In contrast to this study finding, the findings imply that the CBA has higher strength inducing property than the wood waste ash in concrete. CBA could also be said to have lower ASR inducing propensity than wood waste ash since higher strength properties could be attributed to high ASR values. [14] assessed the utilization of cow bone ash as replacement for cement in rigid pavement construction. The study revealed the attainment of optimum compressive strength values of 21.41 N/mm^2 on replacing 20% cement with cow bone ash at the age of 7th day, while 41.28 N/mm^2 was obtained as the optimum compressive strength on replacing 30% cement with cow bone ash at 28th day. However, replacement of 20% cement with CBA in this study gave optimum compressive strength value of 29.92 N/mm^2 at 7th day. Conclusively, it can be said that the CBA used in this study has good ASR inhibiting capability since it has induced better strength properties in the concrete.

The optimum result from this study was obtained at 15% CBA replacement of cement in concrete. These results could be due of flocculation that occurs in the concrete samples as they converge at the 15% CBA replacement and subsequent diverging of the concrete samples on addition of more CBA thereby making their compressive strength to decrease as divergence increases [15].

3.3. Flexural Strength Test

The recommended flexural strength for rigid pavement is 3.5-4.0 N/mm^2 at 28th day of curing [16]. The flexural strength values obtained from this study are as shown in Figure 4.

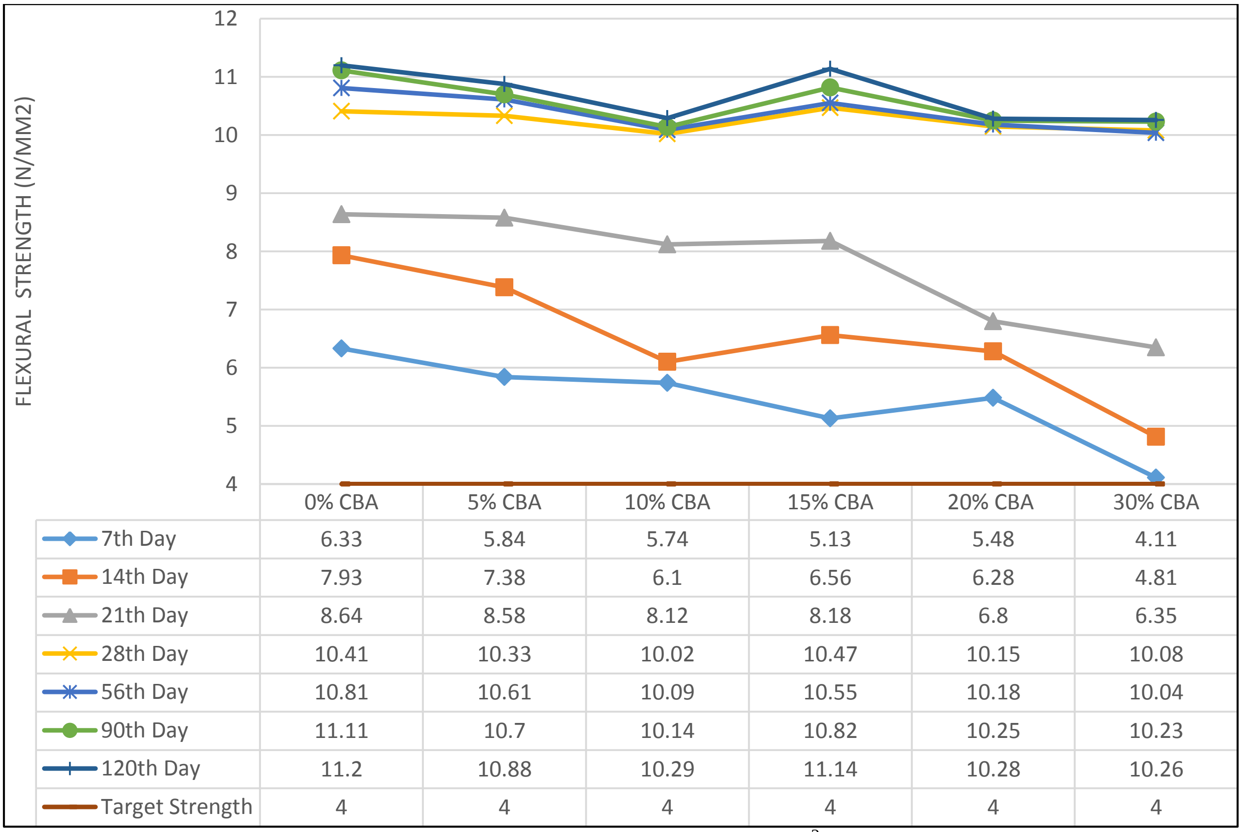


Fig 4. Variation of Flexural Strengths of Cubes (N/mm^2) with Percentages of CBA

Previous studies have shown that ASR contributes to considerable loss in concrete flexural strength [10,17, 18]. Test results from this study showed that an optimum flexural strength value of 5.84 N/mm^2 was obtained at 7th day of curing upon replacement of cement with 5% CBA while at 28th day, flexural strength 7.38 N/mm^2 was obtained at the same 5% replacement level.
Optimum flexural strength value obtained on replacing cement with 15 % CBA in this study was 10.42 N/mm^2 at 28th day and 11.14 at 120th day. The results showed that CBA is a good SCM for reducing ASR.

3.4. Static Structural Modelling of Concrete Pavement Deformation Due to ASR

The input data for the structural modelling is as shown in Table 1. Poisson's ratio value of 0.1 was obtained for high strength concrete.

Table 1. Input data for structural modelling

CBA %	**Compressive Ultimate Strength (Mpa)**	**Poisson Ratio (High Strength Concrete)**	**Original Length (OL) (mm)**	**Length after test (mm)**	**change in length (ΔL) (mm)**	**Cube Area (CA) (mm^2)**	**Tensile Ultimate Strength (Mpa) = $\frac{CA}{FA}$**	**Young Modulus (Pa) = $\frac{FA*OL}{CA*\Delta L}$**	**Force Applied (FA) (N)**
0	$4.98E+10^7$	0.1	148.80	156.61	7.81	22141.44	90.33	1.05E+05	$20*10^5$
5	$4.95E+10^7$	0.1	180.24	185.73	5.49	32486.46	61.56	6.09E+04	$20*10^5$
10	$4.81E+10^7$	0.1	156.18	159.62	3.44	24392.19	81.99	4.41E+04	$20*10^5$
15	$4.83E+10^7$	0.1	151.65	153.62	1.97	22997.72	86.97	2.60E+04	$20*10^5$
20	$4.77E+10^7$	0.1	155.30	157.68	2.38	24118.09	82.93	3.07E+04	$20*10^5$
30	$4.60E+10^7$	0.1	144.65	145.57	0.92	20923.62	95.59	1.27E+04	$20*10^5$

The total deformation of the concrete cubes on impact of 2000 KN force in the negative Y direction with the base of the support taken as fixed supports is shown in Figures 5 to 10. Figure 5 shows that the maximum deformation for the concrete cubes admixed with 0% CBA is 47.045mm. Figure 6 shows a maximum deformation of 33.070mm at 5% CBA replacement, Figure 7 shows a maximum deformation of 20.722mm at 10% CBA replacement. Figure 8 shows a maximum deformation of 11.867mm at 15% CBA replacement, Figure 3.9 shows a maximum deformation of 14.337mm at 20% CBA replacement, while

Figure 10 shows a maximum deformation of 5.542mm at 30% CBA replacement. The deformation of the modelled Portland Cement Concrete (PCC) pavement is also reflected in their decreasing height in relation to the increasing total deformation. This could be related to the deformation in the strata composition of PCC pavements.

The study, reveals that an increase in CBA content generally decreased the effect of ASR on concrete deformation on application of force. This shows that CBA addition will help reduce Portland Cement Concrete Pavement deformation due to ASR in relation to traffic loadings.

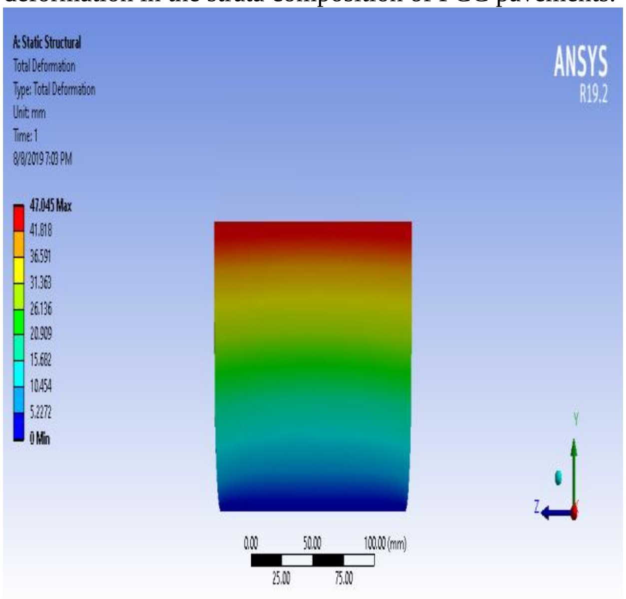


Fig 5. Pavement Deformation at 0% CBA

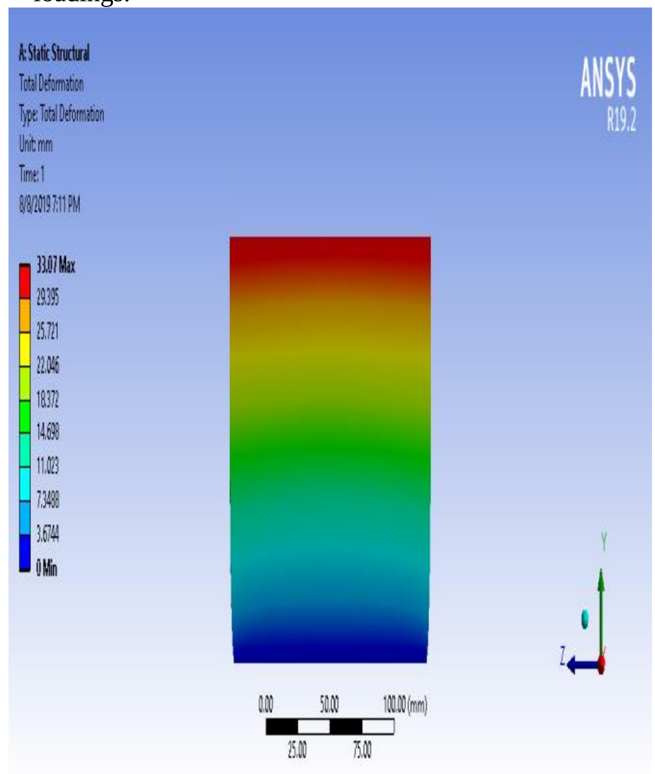


Fig 6. Pavement Deformation at 5% CBA

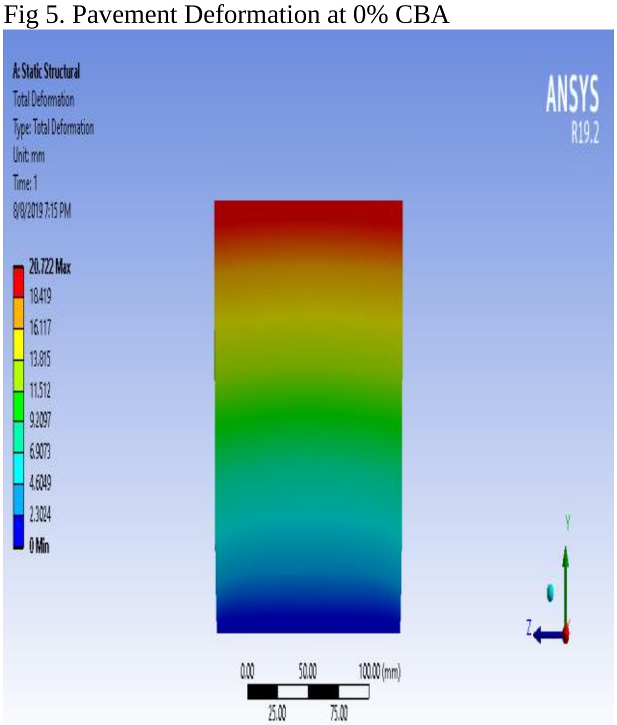


Fig 7. Pavement Deformation at 10% CBA

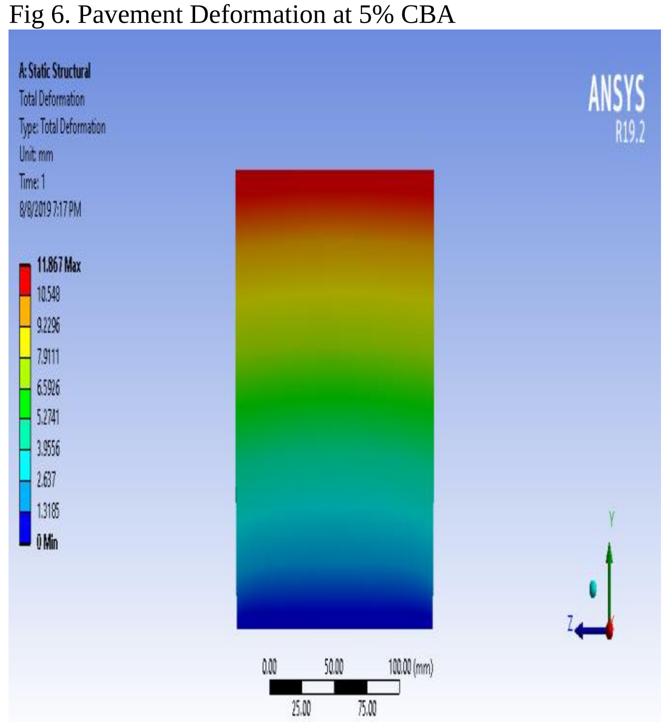


Fig 8. Pavement Deformation at 15% CBA

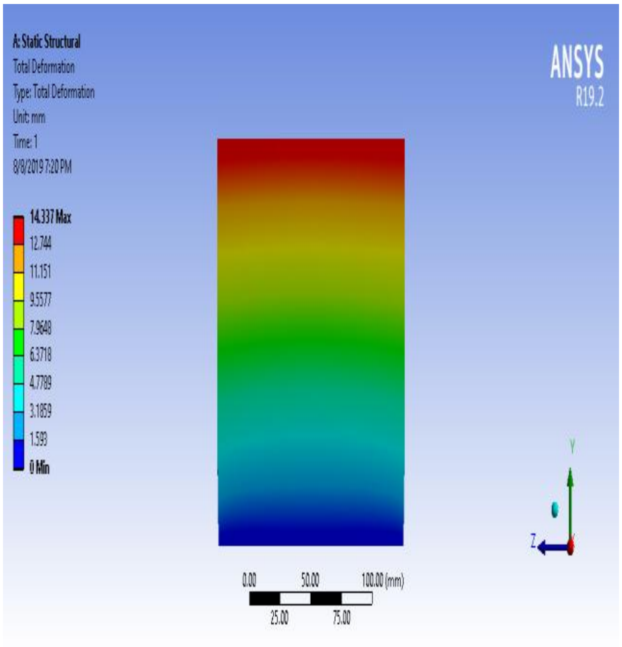


Fig 9. Pavement Deformation at 20% CBA

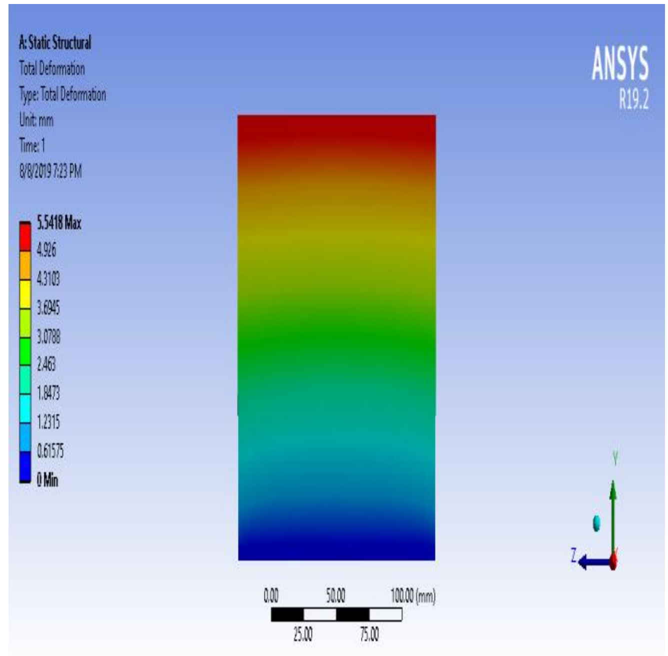


Fig 10. Pavement Deformation at 30% CBA

4. Conclusion

The following conclusions are drawn from the experimental study:
All the concrete cube samples passed the target strength of 48.25 N/mm^2. Optimum compressive strength for the concrete was obtained at 15% CBA replacement of cement with CBA with optimum strength of 57.51 N/mm^2. The increasing compressive strength is associated with reduction in alkali silica reaction. With partial replacement of cement with CBA, rigid pavements will still pass the recommended flexural strength. Optimum flexural strength value obtained on replacing cement with 15 % CBA in this study was 10.42 N/mm^2 at the 28th day and 11.14 at 120th day. The results showed that CBA is a good SCM for reducing ASR. Least structural deformations for the concrete were obtained at 15% and 30% CBA replacement of cement on a 2000KN force application. Therefore, the study concludes that the increasing addition of CBA generally decreases the effect of ASR on concrete deformation on application of force. This shows that CBA addition will help reduce Portland Cement Concrete Pavement deformation due to ASR in relation to traffic loadings.

Conflict of Interest

The authors declare that they have no conflict of interest

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