

Material and Structural Investigation into a Novel Material

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Abstract

Extensive research work has been carried out in the last 50 years or so with the aim of producing more efficient, cost effective and environmentally friendly materials. In the construction industry, this was driven by the growing need for a better and effective way of reducing structural weight and cost. As far as concrete is concerned, which remains one of the most widely used materials in the world, reducing cost in the production of concrete products has led to greater innovation in the use of lightweight concrete such as foam concrete. The latter is known to be in use for about thirty to forty years, but its low quality characteristics has in no small measure hinder its wide industrial application. This paper presents a novel material called GEM-Tech, which early results from laboratory compressing testing of samples suggests that it has formidable material, structural and environmental characteristics, and the potential to result in lightweight elements and huge savings in the construction of structures.

Keywords

Investigating, material, structural, lightweight, Aer-Tech material.

1.1 Introduction

The environmental challenges in reducing the self weight of a structure and its overwhelming high cost demand in the construction industry has undoubtedly considered the light weight cementitious material as an advantage against the bulky use of concrete. In addition to reducing stresses through the life time of structure, by using smaller elements, the total weight of material to be handled during construction is drastically reduced, which consequently increases productivity and reduction on environmental hazards caused by concrete. For this reason was the Aer-Tech material developed.

Aer-Tech has evolved out of concrete but where stone aggregates were replaced with air cells. The Aer-Tech machine equipment uses a patented screw, mixing system and atomised liquid dosing system which produces a regular, consistent homogeneous mix. The atomiser injects air cells as small as 20 micron into the mix replacing the stone aggregate and the mixing screw mixes sand, cement and water with consistency and even distribution, creating a geodesic structure (see Fig.1). The consistent structure created provides the strengths achieved without using any stone aggregates. Importantly, all constituents including air cells are intended to be evenly distributed throughout the mix. This remarkable consistent distribution of air cells creates a geodesic structure, which in effect makes the material unique. However, it is evident that the Aer-tech distinctively possesses the characteristics, different from other lightweight material because, its billions of air cells do not collapse, but coalesce on axial loading, giving the material a high compressive strength. More so, the high strength and low density display of Aer-Tech material gives it, greater potential for use in thermal and acoustic insulation, floating pontoons, making of floor tiles, roof tiles, building walls, slabs and an encasement for toxic waste etc.



Fig. 1 Aer-Tech material being poured in the moulds

Similar studies have shown that base mixes of uniform distribution of air-cells in a plastic mortar give a higher strength (Nambiar and Ramamurthy, 2006). It is also said that bigger pores in a base mix influence the strength. This is correct as the pore system in cement-base material is conventionally, classified as gel-pores, capillary pores, macro-pores due to deliberately entrained air. However, the gel pores do not influence the strength of Aer-Tech material through its porosity. But the capillary pores and other large pores are responsible for reduction in strength and elasticity (Neville and Brooks, 2004).

Several investigations had been carried out on foam concrete, which is defined as self flowing and self compacting concrete, without a coarse aggregate. Over the years, empirical models have been developed to relate the porosity and strength, which focus on extended models of aerated concrete carried out by (Narayaman and Rammamurthy, 2000) and for foam concrete by (Hoff, 1972) and (Kearsely and Wainwright, 2001). These models reflect the effect of porosity on strength and may not adequately represent the pore structure.

According to Cebeci (1981) air entraining agents introduce large air voids and do not alter the characteristics of the fine pore structure of hardened cement paste appreciably (Kearsely and Visagie, 2002) reported that the air-void size distribution is one of the most important micro properties influencing the strength of foam concrete.

The Aer-Tech material is defined as a cementitious material with more than 10% of mechanically entrained air-voids. The paper focuses on highlighting the importance of the machine tuning and adjustments and preliminary tests of compressive strength performance of the Aer-tech material.

According to (Nambiar and Ramamurthy, 2006), fresh state characteristics of foam concrete consistency is an important determining factor in a lightweight mix as it is observed that consistency values either lower (mixture is too stiff causing the bubbles to break) or higher (slurry becomes too thin to hold the bubbles resulting in segregation) than this value lead to an increase in density. This further defined the stability of foam concrete “as the state of mix at which density ratio is closer to unity”. This depends on the consistency of foam concrete is reduced, which is inherent on the foam volume added and for a given density. Following, this occurrence, super-plasticizers are employed to maintain a suitable workability, even though it may reduce the stability of foam concrete (Saucier et. al., 1991, and Cox and Van Dijk, 2002).

1.2 Experimental Programme

1.2.1 Material and mixture composition

The constituent material used to produce Aer-tech material were comprised of: Pro-chem cement conforming to BS8110, pulverized river sand finer than 300μ (specific gravity 2.5), and foam produced by aerating a foaming agent (Aer-Tech Sol) (dilution ratio 1:5 by weight) using an indigenously Aer-tech machine calibrated to a density of 1810kg/m^3 . For this experiment three different types of mixes were used: (1) several specimens were composed of Pro-chem cement, pulverized river sand, distil water and foam (2) a good number of specimens were composed of Pro-chem cement, pulverized river sand, distilled water, foam and a plasticizer and (3) the third types of specimens are composed of Pro-chem cement, water, foam and fibre mesh. Different mixes of the Aer- Tech material were made varying the filler- cement ratio of 4.78:1, 5.83:1 and 4.41:1 design mix. The mixing sequence consisted of a well calibrated Aer-Tech machine, which passes the constituent material from its internally built in conveyor to a mixing chamber, which is designed like a mini batch plant. This process continues until a uniform homogeneous base mix was achieved. The high air content eliminates any tendency to bleed and with good insulation properties, as the mix temperature increases during setting the air expands slightly which ensures good filling and contact in confined voids.

1.2.2 Test Procedure

With a clear objective of assessing the structural behaviour, the author had considered the use of beams as specimens for testing. The base mix from the Aer-Tech machine is poured into beam moulds. The samples are then levelled to achieve good finished surface, left for 24 hours, after which the moulds are uncoupled and carefully placed for air curing in accordance to BS8110 testing procedures. The air-curing period are 14 days, 28 days, 56 days and 6 months period as the case maybe. On completion of air-curing period in compliance with test requirements, a compressive strength test is carried out to ascertain the Aer- Tech resistance capability. In order to study the behaviour Aer-Tech material, normal concrete testing was done to determine the material and structural properties of each type of Aer-Tech and how these properties differ according to different types of mix design. Once the concrete has hardened, it is subjected to a wide range of tests to prove its ability to perform as planned and to determine its characteristics. In the next section are given the results of compressive strength tests carried out on Aer-tech specimens

1.3 RESULTS AND ANALYSIS

1.3.1 Ultimate moment

Three reinforced beam were tested for each Aer-Tech mix of 4.78:1, 4.44:1 and 5., all the beams had the same reinforcement as shown in figure 3.18. the experiment strain and stresses were calculated as shown in table 1.1 and table 1.2

Table 1.1 Experimental strain

Load	Demec1	Demec2	Demec3	Demec4	Demec5
0	0.00908	0.00916	0.009317	0.00943	0.008814
3	0.009084	0.009148	0.00968	0.009793	0.009184
6	0.008979	0.009124	0.00972	0.009829	0.009608
9	0.008854	0.009076	0.009728	0.009874	0.010087
12	0.008685	0.009019	0.009809	0.009994	0.01068
15	0.008568	0.008971	0.009865	0.010172	0.01099
18	0.008447	0.008902	0.00993	0.010377	0.011296
21	0.008274	0.00883	0.009958	0.010446	0.01151
24	0.008116	0.008773	0.009994	0.010615	0.011703
27	0.007923	0.008644	0.010023	0.010704	0.011969
30	0.007742	0.008616	0.010051	0.010909	0.012231

Table 1.2 Experimental compressive stress

Load	Com strsd1	Com Std2	Comstd3	Comstd4	Comstrd5
0	0.2360693	0.238165	0.242251	0.245185	0.229154
3	0.2361741	0.237851	0.251682	0.254615	0.238794
6	0.2334498	0.237222	0.252729	0.255558	0.249796
9	0.2302017	0.235965	0.252939	0.256711	0.262264
12	0.2258009	0.234498	0.255035	0.259854	0.277667
15	0.2227623	0.23324	0.256501	0.264465	0.285735
18	0.2196189	0.231459	0.258178	0.269809	0.293698
21	0.2151133	0.229573	0.258911	0.27159	0.299252
24	0.2110269	0.228106	0.259854	0.275991	0.304281
27	0.2059975	0.224753	0.260588	0.278296	0.311197
30	0.2012824	0.22402	0.261321	0.283639	0.318007

Appreciably, the design ultimate moment for each beam were calculated according to BS 8110-1:1997 cl 3.4.4.4 , as the code propose the following equation:

$$M = 0.156 \times b \times f_{cu}$$

Where:

- M= Ultimate design moment.
- b = width of the section.
- d = effective depth of the tension reinforcement.
- fcu = compressive strength of the concrete.

1.1.1 Mathematical theory for Aer-Tech Beam Test

The Aer-Tech beam test

A (2T10) beam covered with Aer-Tech material

From Tables $E_c = 26 \text{kn/mm}^2$, $d = h - 23 = 180 - 23$

$\Phi = 10 \text{mm}$, $b = 78 \text{mm}$, $d = 157 \text{mm}$

$M = E_s / E_c = 200 / 26 = 7.69$

$$A_s = [\pi * 10^2 / 4 * 2] = 157 \text{mm}^2$$

Now Taking moment about the neutral axis

$$B * y(y/2) = m * A_s(d - y)$$

$$78 * y(y/2) = 7.69 * 157(157 - y)$$

$$39y^2 = 1207.3(157 - y)$$

$$39y^2 + 1207.3y - 189550.1 = 0$$

Solving the above using the quadratic formula.

$$Y = (-b \pm \sqrt{b^2 - 4ac}) / 2a$$

$$Y = 37.79 \text{mm}$$

$$I_{NA} = b \cdot y^3 / 3 + m \cdot A_s (d - y)$$

$$I_{NA} = 1.55 \times 10^6$$

Where, Moment $m = Wa/2$

Table 1.3 Load and moment

Load(KN)	Moment(KNmm)
3	600
6	1200
9	1800
12	2400
15	3000
18	3600
21	4200
24	4800
27	5400
30	6000

Now to obtain the theoretical compressive stress, substitute the derived moment into the equation below;

$$F = M \cdot y / I_{NA}$$

Table 1.4 Load and theoretical compressive stress

Load	Theoretical Compressive stress
0	0
3	0.01463
6	0.02925
9	0.04388
12	0.05851
15	0.07314
18	0.08777
21	0.10239
24	0.11703
27	0.13166
30	0.14628

1.1.2 Aer-Tech mid span deflection of beam

Using the Macaulay's method of mid-span deflection.
Hence, taking the maximum bending moment at section x.

$$M_x = wx/2 - w/2(x-a) - w/2(x-2a)$$

Integrate the above equation.

$$dy/dx = \int w/2x - w/2(x-a) - w/2(x-2a)$$

$$dy/dx = \int wx^2/2 - w(x-a)^2/4 - w(x-2a)^2/4 + A$$

Taking 2nd integration to get the deflection

$$\iint wx^2/2 - w(x-a)^2/4 - w(x-2a)^2/4 + A$$

$$dy^2/dx^2 = \iint wx^3/12 - w(x-a)^3/12 - w(x-2a)^3/12 + Ax + B$$

Boundary condition

$$X=0; \delta = 0;$$

$$X=L ; \delta = 0; X = 3a$$

By substitution.

$$Y = 23wl^3/1296EI$$

Thus, deflection y for the Aer-Tech beam = $23wl^3/1296EI$.

Whilst, table 1.3 shows values of central deflection and theoretical deflection which is derived by inputting varying loads used during the experimental process.

Table 1.5 Load central deflection and theoretical stress

Load	Central deflection	Theoretical deflection
0	0	0
3	0.5	2.283
6	0.91	4.566
9	1.36	6.848
12	1.87	9.132
15	2.28	11.414
18	2.77	13.697
21	3.48	15.98
24	3.93	18.263
27	4.59	20.54
30	5.22	22.829

Calculating the ultimate load using BS8110

Taking the following from tables;

$$f_{cu}=30\text{N/mm}^2, f_v= 460\text{N/mm}^2, f_{cm}=30+ 1.64=43.12$$

$$B=78\text{mm}, A_s= 157\text{mm}^2 \text{ and } d = 157\text{mm}$$

Hence,

$$\begin{aligned} M_u &= 0.156 f_{cu} b d^2 \\ &= 0.156 \times 30 \times 78 \times (157)^2 = 8.421 \times 10^6 \text{Nmm} \\ &= 8.977 \times 10^6 \end{aligned}$$

Now substituting m_u in

$$\begin{aligned} W &= 2m_u/a \text{ (where } a=500) \\ W &= 2 \times 8.997 \times 10^6 / 500 \\ W &= 35.99 \end{aligned}$$

Therefore, theoretical ultimate design load = 35.99KN, whereas experimental failure load is 38.7KN

The above results confirms that experimental failure load capacity achieved is higher than the theoretical ultimate design load in accordance to British standards, this could be because Aer-Tech material has lower elastic modulus than normal concrete, thus it is less stiff than normal concrete. It should be observed that the constant 0.156 in the above equation comes out by multiplying the ultimate stress block of the concrete by the lever arm, and the BS 8110-1997 state the following equation to calculate the ultimate stress block:

Table 1.6 Theoretical stress and experimental stress

Load	Theoretical compressive Stress	Experimental Compressive stress for d1	Experimental Compressive stress for demec5
0	0	0.2360693	0.229154
3	0.014628	0.2361741	0.238794
6	0.02925	0.2334498	0.249796
9	0.04388	0.2302017	0.262264
12	0.05851	0.2258009	0.2777667
15	0.07314	0.2227623	0.285735
18	0.08777	0.2196189	0.293698
21	0.10239	0.2151133	0.299252
24	0.11703	0.2110269	0.304281
27	0.131655	0.2059975	0.31197
30	0.14628	0.2012824	0.318007



Figure 1.3 Mix three local failure



Figure 1.4 Sinking of load in Mix three experiment

1.2 Beam behaviour in service and collapse

Considerable steps had been taking by the researcher to properly assess structural performance of Aer-Tech novel material. Interestingly, the Aer-Tech beam test had provided a clearer view of how the material behave in serviceability and collapse of its reinforced beams. Ultimately, all beams showed typical structural behaviour in flexure. Also, during the test of the three beams no horizontal cracks were observed at the level of the reinforcement, which confirms non occurrence of bond failure. However, vertical flexural cracks were observed in the constant

moment region and final failure occurred due to crushing of compression Aer-Tech material and breaking of steel reinforcement on application of significant amount of ultimate deflection.

1.2.1 Deflection Behaviour Of Aer-Tech Singly Reinforced Beam

Figure 1.5 and table 1.5 shows that experimental deflection is lower than the theoretical deflection. The illustration of load against deflection graph confirms that in both experimental and theoretical results, the relationship between load and deflection is linear. Which further illustrate that as load increases the deflection in both cases increases, because tensile stresses increases down the neutral axis to the bottom of the beam. where the reinforced bars are positioned. More so, from material investigation of Aer-Tech material, this novel material is said to be a less dense and porous material, which practically influence the stiffness of Aer-Tech material. Essentially, these effect had made Aer-Tech to exhibit low modulus of elasticity, which primarily is governed by the stiffness of coarse aggregate in mix. Consequently, the result of deflection of Aer-Tech reinforced beam under the design service load is acceptable, irrespective of low modulus of elasticity, since its values were within the serviceability limit of BS 8110-1:1997 cl 3.4.6.3, as the code specify that the deflection should be less than [Span/250] and for this experiment [1500/250= 6mm]. Comparably, it is observed that Aer-Tech reinforced beam exhibit similar behaviour to that of other lightweight concrete beams (Swamy and Ibrahim, 1975).

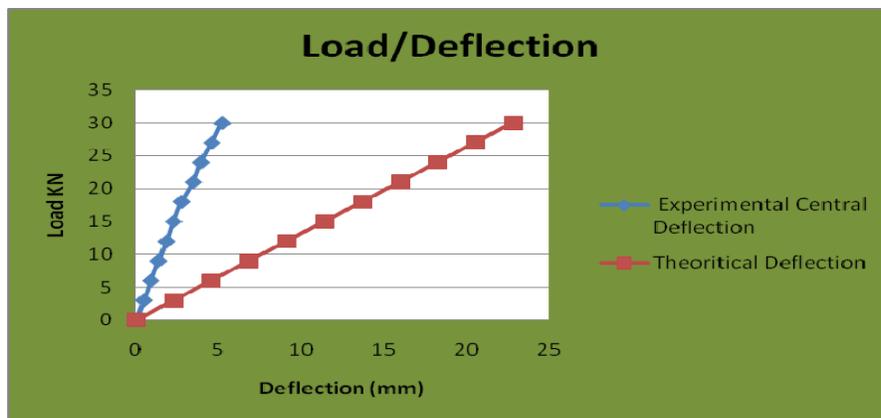


Figure 1.5 Experimental and theoretical deflection values for reinforced beam mix one

1.2.2 Reinforced Aer-Tech Material Strains and compressive stress

Specifically, the strain results of reinforced Aer-tech beam were measured in every load increments. The results of strain distribution are presented in table 1.1. More so, at the given service load of 3KN to 30KN the strain results ranges from $2283 \times 0.403 \times 10^5$ to $3035 \times 0.403 \times 10^5$. Whilst, the measured strain just prior to failure varied from $3198 \times 0.403 \times 10^5$ to $3231 \times 0.403 \times 10^5$ respectively. Fig 1.7 shows the strain distribution effect in Aer-Tech material on application of load. The strain diagram confirms that strain occurs across the depth of the beam. The illustration in fig5.20 show clearly that demec strain reading does reduces at the top on increasing load for demec 1 and 2, but increases as load increases on demec 3,4 and 5. This behaviour is supported by the bending theory that plane section of a structural member remain plane after straining. Importantly, results obtained are consistent with works of other researchers (Delsye C.L. Teo, Md. Abdul Mannan and John V. Kurian, 2006)

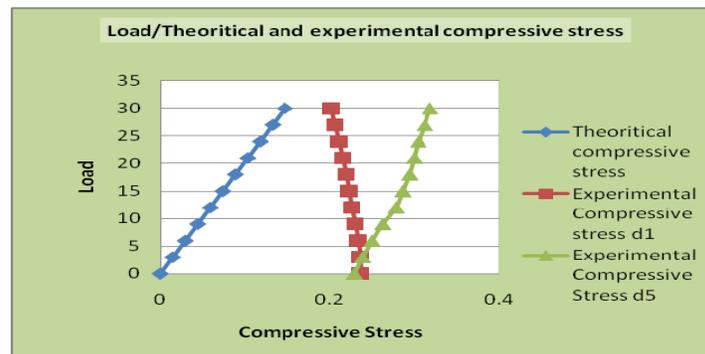


Figure 1.6 Error! No text of specified style in document..1 Against Theoretical and experimental compressive Stress

The illustration on figure 1.6 shows that the theoretical compressive stress and experimental stress of demec 5 are directly proportional to load application. Explicitly, what happens is that the greater the load application on an aer-Tech material the higher the compressive stress effect developed. More so, this significant structural behaviour of Aer-Tech material do lead to first appearance of cracks at the bottom of the reinforced Aer-Tech beam. Intrinsically, as the load increases from 3KN to 12KN the initial slight crack appearance becomes more noticeable. These cracks are simply known as diagonal tension cracks. The structural effect of Aer-Tech material conforms with the analogy as stated in (Moseley, Hulse and Bungey.1999) which state that wherever tension occurs in a material. These confirms areas of inevitable cracks within same place.

Comparatively, the values from the table 1.6 and fig 1.6 was drawn, using the values of experimental strain at the top surface of the beam (demec 1) and the bottom base of the beam (demec 5) by calculating the theoretical result using $f = E_c \times \epsilon_c$ from the figure and the table, it could be observed that the theoretical results are lower than the experimental ones and that could be because the material matrix is getting disturbed, or it could be because the theoretical values are values without any losses that could be due changing the area of the beam surface or due to shrinking.

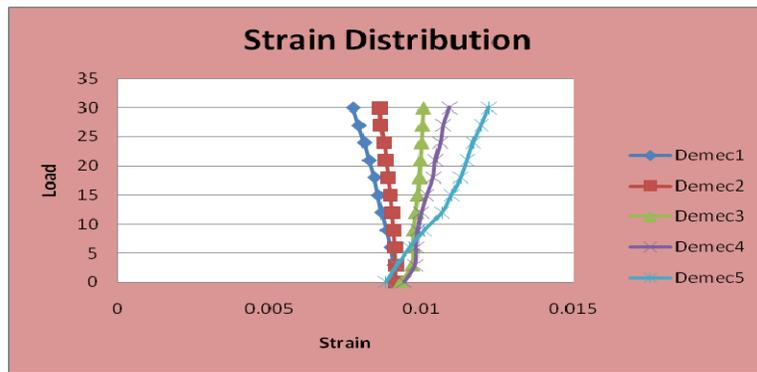


Figure 1.7 Error! No text of specified style in document..2 Depth-strain for reinforced beam (mix one)

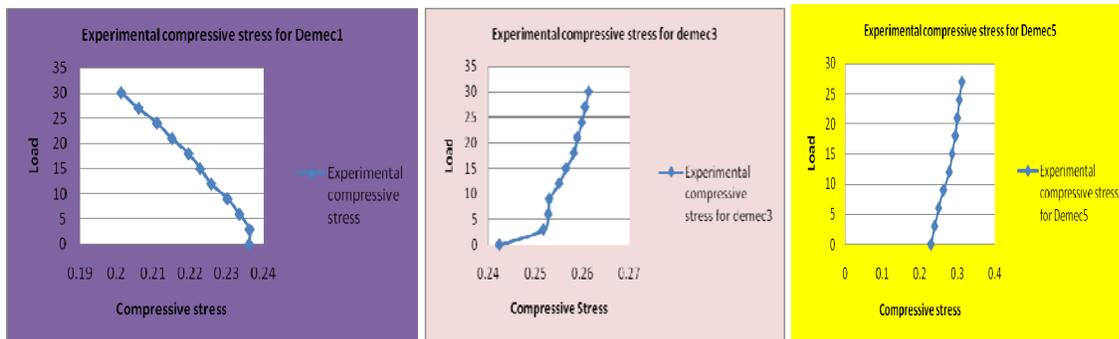


Figure 1.8 Load Against compressive Stress for Demec 1,3 & 5

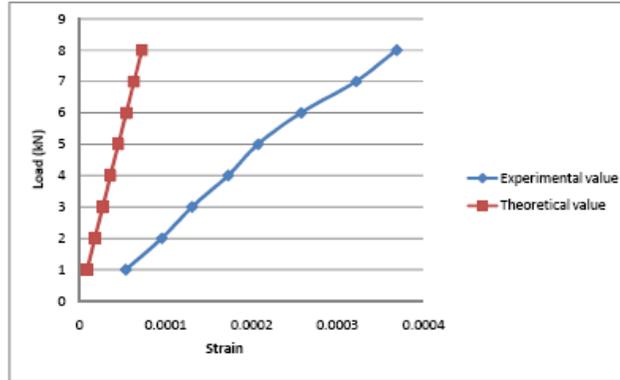


Figure 1.9 Error! No text of specified style in document..3 Load-strain for reinforced beam (mix one)

1.2.3 Reinforced Aer-Tech beam Ductility Behaviour

Ultimately, the ductility of reinforced Aer-Tech beam is primarily important in justifying structural capability of the material. Since, from structural standard it is paramount for a ductile structural material to undergo large deflection at near maximum load carrying capacity, by providing ample warnings to an impending failure. Table 5 shows that ductility of tested Aer-Tech reinforced beam. Thus the displacement ductility ratio is taken in terms of $\mu = \Delta_u / \Delta_y$, which is the ratio of ultimate moment to first yield deflection. Where Δ_u is the deflection at ultimate moment and Δ_y is the deflection when the steel yield. In general, high ductility ratios confirms that structural member is capable of undergoing large deflection prior to failure. Consequently, the result of this investigation on Aer-Tech reinforced beam ductility, shows that Aer-Tech material posses relatively good ductile characteristics as beam shows clear signs of cracks on beam long before failure. This can be attributed to its inherent pore structure formation due foam content.

1.3 Modes of failure

Aer-Tech reinforced beams had two different modes of failure. Figure 2.0 and figure 2.1 show modes of failure for mix four and mix two respectively. As is shown from figure 2.1, the beam failed in total bending. The ultimate experimental failure load of Aer-Tech material is 38.7 kN, whilst the theoretical calculated ultimate load is 35 kN. The nearness of experimental and theoretical failure load confirms structural capability of Aer-Tech material. Appreciably, the theoretical failure load calculated in accordance to BS8110, obviously lower than the failure load derive from the lab. Their differences are probably caused by the assumption that the compressive and tensile forces were equal. However, the strain distribution diagram shows that strain at the bottom is greater than the strain at the top. Apparently, what happens is the theoretical failure may not have taken into account that the tensile stress is still subjected to the reinforcement bars after the concrete has cracked. Whilst, in case of the experimental failure load a higher experimental failure load was achieved, since the steel reinforcement in the beam continue taking the tension developed until it reaches its ultimate yielding point where it no longer could with stand any further load increase, it therefore breaks at a higher ultimate failure load as compared to theoretical failure load. But by measuring the angle of the crack in figure 2.0 it was found to be 35° which indicated that the beam failed in combined mechanism of bending and shear stresses.



Figure 2.0 Error! No text of specified style in document..4 Mode of failure for reinforced beam mix four



Figure 2.1 Error! No text of specified style in document..5 beam on loading

1.4 Conclusions

The experimental investigation of reinforced Aer-Tech beam has shown that Aer-Tech structural behaviour is comparable to other lightweight concrete. Below are some of the conclusion made, based on current experimental results.

- Structural assessment Aer-Tech material has shown that the Aer-Tech beam suffered tension at the bottom and compressive forces at the top, which resulted in the diagonal tension cracks being produced mid span at the bottom of the beam.
- Also result of reinforced Aer-Tech beam had shown that as load application increases on beam the tension on the steel reinforcement increases until failure occurs.
- The experimental performance of a 23 days Aer –Tech beam test, has shown that the experimental ultimate moments of Aer-Tech reinforced beam is 3.62% higher than the theoretical ultimate moments.
- The deflection of Aer-Tech material calculated using BS8110 under service load can be used to give reasonable predictions. More so, the deflection under the service load for singly reinforced beams were within their allowable limit provided by BS8110.
- Importantly, the Aer-Tech reinforced beam test gave a high elastic modulus of 25.99 MPa, an indication Aer-Tech material has flexural capability.

Acknowledgement

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References

- British Standards BS8110 (2000). Testing Hardened Concrete: Part 14.
- Cebeci, O.Z. (1981). “Pore structure of air-entrained hardened cement paste”. *Cement and Concrete Research* **11**, pp. 257–265.
- Cox, L. and Van Dijk, S. (2002). “Foam concrete: a different kind of mix”. *CONCRETE*, Vol.36, No.2, pp.54-55.
- Hoff, G.C. (1972). “Porosity–strength considerations for cellular concrete”. *Cement and Concrete Research* **2**, pp. 91–100.
- Keasel, E. P. and Visagie, M. (1999). “Micro-properties of foamed concrete”. *R.K. Dhir, N.A. Handerson (Eds.), Specialist techniques and material for construction, Thomas Telford.*
- Nambiar, E. K. K. and Ramamurthy, K. (2006). “Air-void characterization of foam concrete”. *Elsevier*, 37 221-230.
- Narayanan, N. and Ramamurthy, K. (2000). “Structure and properties of aerated concrete: a review”. *Elsevier Science Ltd.*
- Neville, A.M. and J.J. Brooks, J.J. (2004). “*Concrete Technology*”, Pearson Education Pvt. Ltd., Singapore.
- Saucier, F., Pigeon, M. and Cameron, G. (1991). “Air-Void Stability, Part V: Temperature, General Analysis and Performance Index,” *ACI Materials Journal*, V. 88, No. 1, pp.25-36.