



Effect of Multi-Walled Carbon Nanotubes on the Mechanical Properties of Fly Ash-Modified Foam Concrete: Experimental Investigation and Numerical Beam Analysis

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Abstract

Foam concrete is valued as a lightweight, thermally insulating material, but its low compressive, tensile and flexural strengths restrict its structural use. This study examines the effect of multi-walled carbon nanotubes (MWCNTs) on the mechanical properties of foam concrete of 1500 kg/m³ target density. The MWCNTs were dispersed by ultrasonication in a polycarboxylate-ether superplasticizer solution and replaced 0.1–0.5% of the cement by mass, while Class F fly ash replaced 0–80% of the fine aggregate (water–cement ratio 0.3; sand–cement ratio 2.5). Compressive strength, split tensile strength, modulus of elasticity and flexural strength were evaluated at 28 days. All four properties improved with MWCNT addition up to an optimum dosage of 0.3% (with 40% fly ash replacement), beyond which agglomeration of the nanotubes reduced performance. At the optimum, the compressive strength was 19.61 MPa, about 40% higher than that of conventional foam concrete (14.01 MPa) and about 31% higher than that of M15 normal concrete (15 MPa). The load–deflection response of three simply supported beams (150 × 200 × 1800 mm) made of normal concrete (B1), conventional foam concrete (B2) and MWCNT foam concrete (B3) was then simulated in SAP2000. The results show that MWCNTs are a promising nano-additive for strengthening foam concrete, provided that effective dispersion is achieved.

Keywords: foam concrete; multi-walled carbon nanotubes; fly ash; ultrasonication; mechanical properties; SAP2000

1. Introduction

Foam concrete, also referred to as cellular or aerated lightweight concrete, is produced by introducing a preformed, stable foam into a cement-based slurry or mortar so that a system of discrete air voids is formed in the hardened matrix [1,2]. By controlling the foam dosage, oven-dry densities in the range of roughly 400–1600 kg/m³ can be obtained [3]. The resulting material combines low self-weight, high flowability, self-levelling behaviour without the need for compaction, and good thermal insulation, which makes it attractive for partitions, insulation layers, void filling and lightweight structural elements [3–5].

The same air-void system that gives foam concrete its low density, however, also lowers its compressive, tensile and flexural strengths and makes it brittle [1,6]. These limitations have restricted its use in load-bearing applications and have motivated efforts to improve the strength of the matrix without sacrificing the lightweight character of the material.

Nanotechnology offers one such route. Nano-sized additives, with dimensions of the order of 10^{−9} m, possess a very high surface-area-to-volume ratio and hence a high potential for chemical and physical interaction with cement phases [7]. Their effective use in concrete

nevertheless depends on solving several problems, namely proper dispersion, upscaling to practical batch sizes, and an acceptable cost–benefit ratio [7]. Nano-modification of foam concrete has so far been explored with materials such as nano-silica [13].

Carbon nanotubes (CNTs) are cylindrical allotropes of carbon whose walls consist of rolled graphene sheets [8]. They are classified as single-walled (SWCNT), double-walled (DWCNT) and multi-walled (MWCNT) nanotubes, and their properties depend on the rolling angle and diameter of the graphene sheet. MWCNTs combine a high aspect ratio, very high tensile strength [12] and a large specific surface area with a lower cost than SWCNTs, which makes them the most practical CNT type for cementitious composites (Fig. 1). The main obstacle to their use is the strong van der Waals attraction between tubes, which causes them to form bundles and agglomerates in the mix. Ultrasonication combined with surfactants or superplasticizers has been shown to improve dispersion in cement-based materials [9,10], and the influence of CNT dosage and water–cement ratio on mortar properties has also been examined [11].

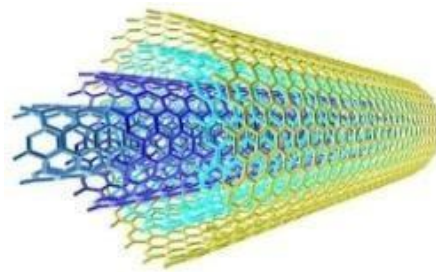


Fig. 1. Illustration of multi-walled carbon nanotubes (MWCNTs).

To the authors' knowledge, the combined effect of MWCNT dosage and fly ash replacement of fine aggregate on the mechanical behaviour of foam concrete has received limited attention. This study therefore aims to (i) establish an effective procedure for dispersing MWCNTs in a foam concrete mix; (ii) determine the compressive strength, split tensile strength, modulus of elasticity and flexural strength of foam concrete containing 0.1–0.5% MWCNT and 0–80% fly ash replacement of sand; and (iii) compare, by numerical modelling in SAP2000, the load–deflection behaviour of beams made of normal concrete, conventional foam concrete and MWCNT-reinforced foam concrete.

2. Materials and methods

2.1 Materials

Ordinary Portland cement (OPC) of 53 grade, ASTM Type I, was used in all mixes. Class F fly ash conforming to ASTM C618 [16] was used as a partial replacement of fine aggregate. The chemical compositions of the cement and the fly ash are given in Table 1. MWCNTs were

used as a partial replacement of cement and were dispersed in a polycarboxylate-ether-based superplasticizer. Foam was generated from a protein-based foaming agent.

Table 1. Chemical composition of OPC and Class F fly ash.

Constituent (% by mass)	OPC	Class F fly ash
Silicon dioxide (SiO_2)	21.60	54.90
Aluminium oxide (Al_2O_3)	4.13	25.80
Ferric oxide (Fe_2O_3)	4.57	6.90
Calcium oxide (CaO)	64.44	8.70
Magnesium oxide (MgO)	1.06	1.80
Sodium oxide (Na_2O)	0.11	0.30
Potassium oxide (K_2O)	0.56	0.10
Sulphur trioxide (SO_3)	1.74	0.60
Loss on ignition	0.76	0.20

2.2 Dispersion of MWCNTs

The full potential of MWCNTs as reinforcement is limited by their tendency to agglomerate and by weak interfacial interaction between the tubes and the matrix. Because the nanotubes provide an exceptionally large number of particles and a very large surface area, uniform dispersion in a cementitious matrix is difficult. In this study the nanotubes were dispersed by ultrasonication. Ultrasonication applies ultrasound energy to agitate particles in a liquid. In the laboratory it is carried out with an ultrasonic bath or an ultrasonic probe (sonicator). The propagating sound waves create alternating compression and rarefaction cycles in the liquid; the resulting cavitation produces local shear forces that peel individual tubes from the outer surface of the bundles and separate them. The method is most effective in low-viscosity liquids such as water, acetone and ethanol. Here, a bath sonicator (Fig. 2) was used, and a polycarboxylate ether superplasticizer solution served as the dispersing medium.



Fig. 2. Ultrasonication of MWCNTs using a bath sonicator.

2.3 Foam generation

Foam was produced with a foam generator. Foaming agents are broadly of two types, protein-based and synthetic, with unit weights of foam solution of 80 g/L and 40 g/L, respectively. Protein-based foam generally gives higher strength than synthetic foam and was therefore



adopted. The foaming agent was diluted with water at a ratio of 1:40 and fed to the generator together with compressed air at a pressure of 6 psi, which produced a stable, uniform foam.

2.4 Mix proportions

The water–cement (w/c) ratio and the sand–cement (s/c) ratio were fixed at 0.3 and 2.5, respectively. The target density was selected by trial and error: it was initially set at 500 kg/m³ and increased in accordance with the intended field application, and a target density of 1500 kg/m³ was finally adopted. Five series of mixes (Series I–V) were prepared in which MWCNTs replaced 0.1, 0.2, 0.3, 0.4 and 0.5% of the cement by mass. Within each series, fly ash replaced 0, 20, 40, 60 and 80% of the sand by mass (Mixes 1–5). The complete mix compositions are listed in Table 2. In all mixes the foam content was 18.48 kg/m³, the superplasticizer volume was 4.8 L/m³ and the water volume was 143.23 L/m³.

Table 2. Composition of the foam concrete mixtures (per m³).



Series	MWCNT (% of cement)	Mix	Fly ash (% of sand)	Cement (kg)	Sand (kg)	Fly ash (kg)
I	0.1	1	0	492.94	1233.56	0
		2	20	492.94	986.85	246.71
		3	40	492.94	740.14	493.42
		4	60	492.94	493.42	740.14
		5	80	492.94	246.71	986.85
II	0.2	1	0	492.44	1233.56	0
		2	20	492.44	986.85	246.71
		3	40	492.44	740.14	493.42
		4	60	492.44	493.42	740.14
		5	80	492.44	246.71	986.85
III	0.3	1	0	491.95	1233.56	0
		2	20	491.95	986.85	246.71
		3	40	491.95	740.14	493.42
		4	60	491.95	493.42	740.14
		5	80	491.95	246.71	986.85
IV	0.4	1	0	491.46	1233.56	0
		2	20	491.46	986.85	246.71
		3	40	491.46	740.14	493.42
		4	60	491.46	493.42	740.14
		5	80	491.46	246.71	986.85
V	0.5	1	0	490.96	1233.56	0
		2	20	490.96	986.85	246.71
		3	40	490.96	740.14	493.42
		4	60	490.96	493.42	740.14
		5	80	490.96	246.71	986.85

Fly ash replaces sand by mass; MWCNT content is the percentage of cement replaced in each series.

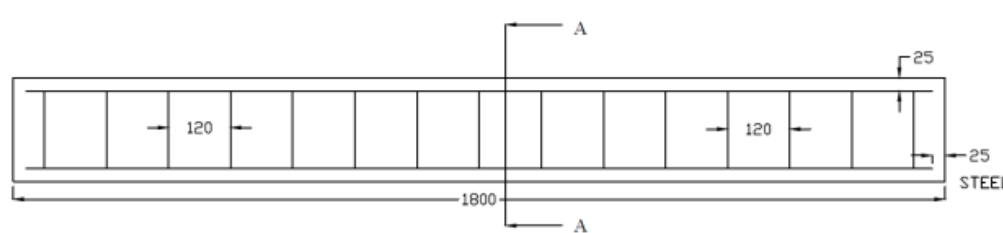
2.5 Mixing, casting and testing of specimens

Foam concrete was produced in the laboratory in a paddle mixer by adding preformed foam to a base mix. The binder and water were first mixed until a homogeneous base mix was obtained, after which the dispersed MWCNTs were added. The required mass of foam was then generated, added immediately to the base mix and mixed for the minimum time needed for the foam to disappear from the surface and be distributed uniformly through the mix.

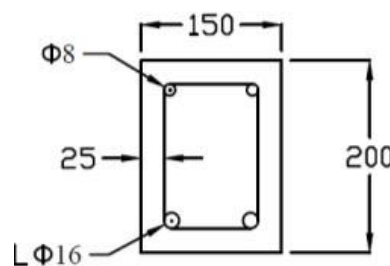
Cubes of $150 \times 150 \times 150$ mm were cast for compressive strength, cylinders of 150 mm diameter $\times$ 300 mm height for split tensile strength and modulus of elasticity, and prisms of $100 \times 100 \times 400$ mm for flexural strength. All properties were determined after 28 days.

2.6 Beam specimens

Three beams of $150 \times 200 \times 1800$ mm were considered: normal concrete of characteristic compressive strength equivalent to that of the foam concrete (B1), conventional foam concrete (B2) and MWCNT-reinforced foam concrete (B3). The reinforcement detail was the same for all beams (Fig. 3): 25 mm clear cover on all sides, two 16 mm diameter main bars, two 8 mm diameter hanger bars, and fifteen 8 mm diameter two-legged stirrups at 120 mm spacing. The normal concrete (grade M15) was proportioned according to IS 10262:2009 [15]; the mix proportions are given in Table 3.



(a) Longitudinal section.



(b) Cross-section A–A (dimensions in mm).

Fig. 3. Reinforcement details of the beams (all dimensions in mm).

Table 3. Mix proportions of M15 normal concrete.

Material	Quantity (kg/m ³)
Cement	394.00
Fine aggregate	743.09
Coarse aggregate	1114.63
Water	197.00
Water–cement ratio	0.50

3. Results and discussion

The specimens were tested at 28 days. In Figs. 4–7, “FC” denotes the mix without fly ash and “FA 20%”–“FA 80%” denote the percentage of sand replaced by fly ash; each curve corresponds to one MWCNT dosage (CNT 0.1–0.5% by mass of cement).

3.1 Compressive strength

Fig. 4 shows the effect of MWCNT dosage and fly ash content on compressive strength. For a given foam volume, MWCNT addition raised the compressive strength up to a dosage of 0.3%. At 0.4% and 0.5% the strength decreased again, which is attributed to agglomeration of the nanotubes in the superplasticizer medium, i.e. to the limited capacity of the dispersing medium to separate the tubes at higher dosages. Increasing the fly ash content also raised the strength up to an optimum value, beyond which the strength decreased because of the breakdown of the air-void structure of the matrix. The highest compressive strength was obtained with 0.3% MWCNT and 40% fly ash replacement.

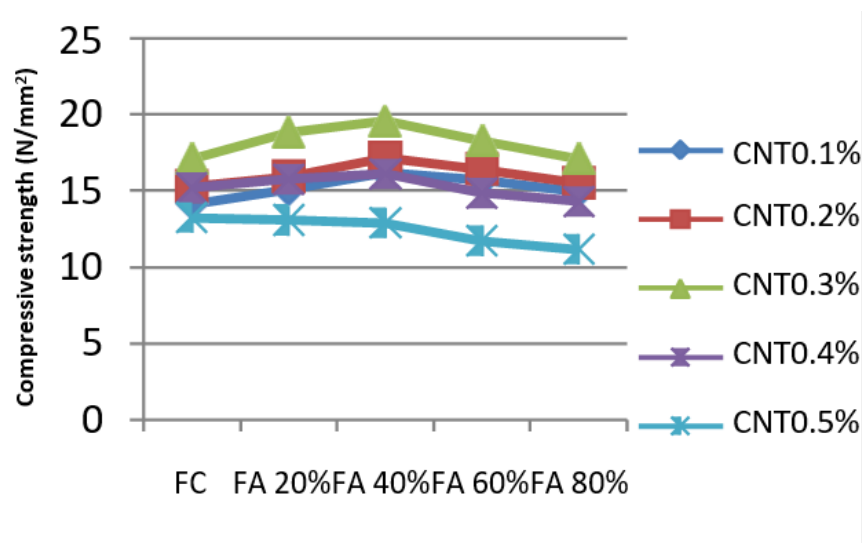


Fig. 4. Compressive strength of foam concrete mixes.

3.2 Split tensile strength

The split tensile strength followed the same trend as the compressive strength (Fig. 5), and the maximum value was again obtained at 0.3% MWCNT. The improvement is consistent with the ability of well-dispersed nanotubes to bridge microcracks in the matrix.

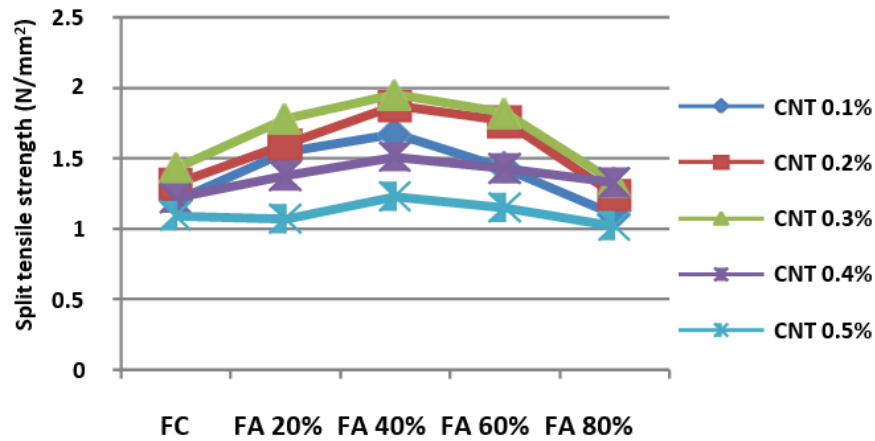


Fig. 5. Split tensile strength of foam concrete mixes.

3.3 Modulus of elasticity

The modulus of elasticity of MWCNT-reinforced foam concrete was higher than that of conventional foam concrete (Fig. 6), with the same dependence on MWCNT dosage and fly ash content as the strength.

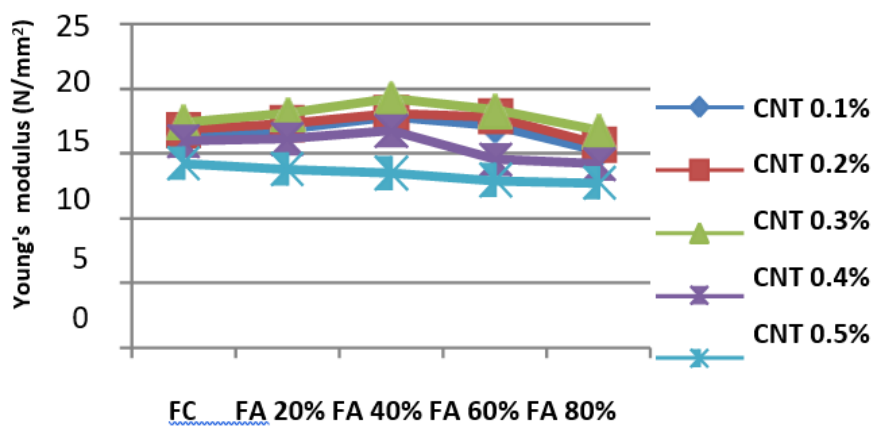


Fig. 6. Modulus of elasticity of foam concrete mixes.

3.4 Flexural strength

The flexural strength of MWCNT foam concrete was higher than that of conventional foam concrete (Fig. 7). Because of the air voids in the matrix, however, foam concrete remained more brittle than normal concrete.

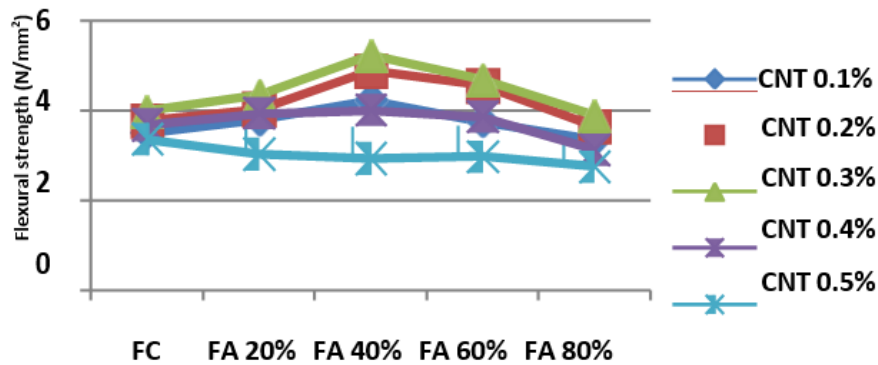


Fig. 7. Flexural strength of foam concrete mixes.

4. Numerical analysis of beams

The optimum compressive strength, modulus of elasticity and density of the MWCNT foam concrete were used to model the $150 \times 200 \times 1800$ mm beams in SAP2000 (Fig. 8). The material properties adopted for the three beams are given in Table 4. The moduli of elasticity listed correspond to $E_c = 5000\sqrt{f_{ck}}$ (IS 456:2000 [14]).

Table 4. Material properties adopted in the numerical model.

Property	Normal concrete (B1)	Conventional foam concrete (B2)	MWCNT foam concrete (B3)
Compressive strength, f_{ck} (MPa)	15.00	14.01	19.61
Modulus of elasticity, E_c (MPa)	19364.91	18714.97	22141.59
Poisson's ratio	0.20	0.20	0.20
Density (kg/m^3)	2500	1500	1500

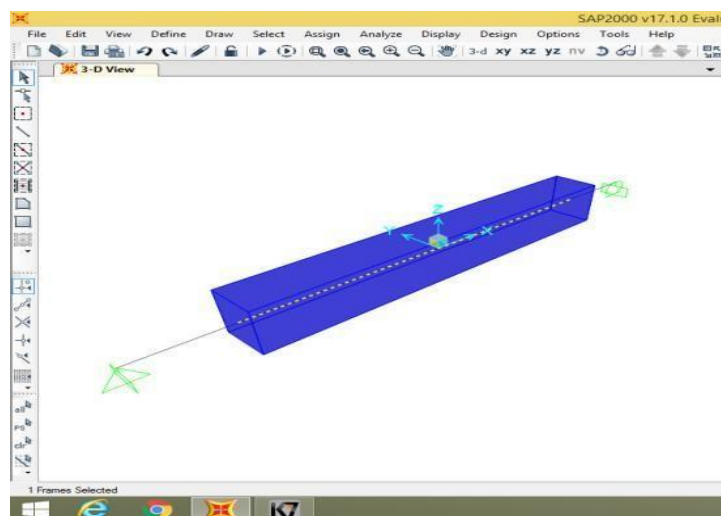


Fig. 8. Finite element model of the beam in SAP2000.

The beams were modelled as simply supported and loaded with two symmetric point loads, applied incrementally. The maximum deflection at mid-span was recorded at each load step and plotted against the applied load (Fig. 9).

The curves for B1 (normal concrete) and B2 (conventional foam concrete) are nearly coincident. At the maximum load of about 100 kN, B1 and B2 deflected by roughly 10 mm, whereas B3 (MWCNT foam concrete) deflected by roughly 11 mm. A smaller deflection might have been expected for B3 in view of its higher modulus of elasticity (Table 4); this result therefore needs to be verified against experimental beam tests, which are planned.

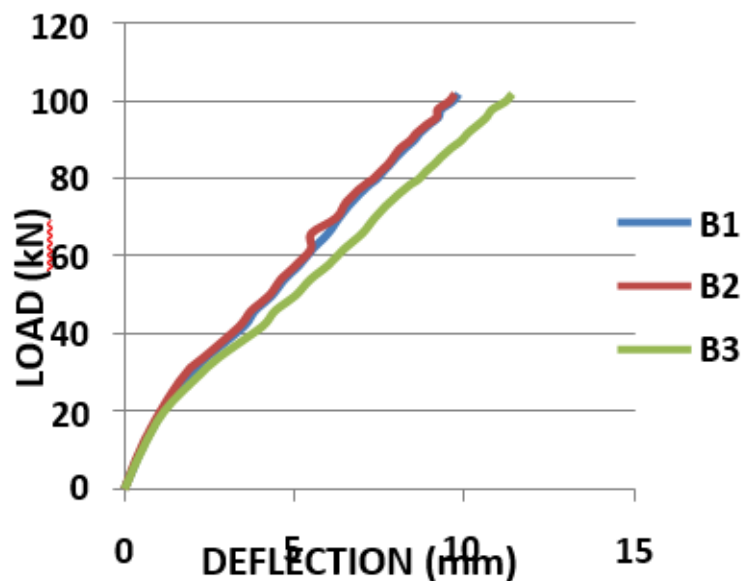


Fig. 9. Load–deflection curves of beams B1, B2 and B3 obtained from the SAP2000 analysis.

5. Conclusions

The following conclusions are drawn from this investigation on foam concrete containing MWCNTs and fly ash:

1. Replacing cement with MWCNTs increased the compressive strength, split tensile strength, modulus of elasticity and flexural strength of foam concrete. The optimum combination was 0.3% MWCNT by mass of cement with 40% fly ash replacement of fine aggregate.
2. At the optimum, the MWCNT foam concrete (1500 kg/m^3) reached a compressive strength of 19.61 MPa, about 40% higher than conventional foam concrete (14.01 MPa) and about 31% higher than M15 normal concrete (15 MPa), while being 40% lighter than normal concrete (2500 kg/m^3).
3. MWCNT dosages above 0.3% reduced the properties because the nanotubes agglomerated in the superplasticizer dispersing medium. Improved dispersion is needed to exploit higher dosages.
4. Fly ash contents above the optimum reduced the strength, which is attributed to disruption of the air-void structure.
5. MWCNT foam concrete remained brittle, which is a limitation for structural applications.



6. In the SAP2000 analysis, the normal and conventional foam concrete beams showed nearly identical load–deflection behaviour, while the MWCNT foam concrete beam deflected slightly more at the same load (about 11 mm versus 10 mm at 100 kN). Experimental beam tests are required to validate this behaviour.

Future work should include microstructural characterisation (e.g. SEM and porosity measurements), other dispersion techniques, durability and thermal performance, and experimental flexural testing of the reinforced beams.

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