REGULAR ARTICLE

Influence of Nano-Carbon Additives on the Mechanical Properties of Cementitious Composites: A Study on Static and Dynamic Modulus Variations

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This Effect of Nano-carbon additives on mechanical performance and durability of cementitious composites in oi terms of static and dynamic modulus is studied. A Nano carbon powder was admixed in 5%, 10% and 15 % levels as a cement replacement in M20, M25 and M30 concrete grades and the mechanical properties were determined for curing ages of 14, 28 and 84 days. These results show that 5% Nano-carbon addition has improved static and dynamic modulus by increasing stiffness, fatigue resistance and load bearing capability. However, modulus values decreased above 10 % and 15 % replacement levels (due to agglomeration effects and non-uniform dispersion of carbon particles to matrices). A statistical analysis of modulus variations revealed lower variability at 5 % replacement, indicating good performance. Those findings confirm that at controlled dosages, Nano carbon additives improve mechanical properties and are suitable for high-performance concrete (and) bridges, pavements, and smart infrastructure. This study highlights the feasibility of using nano carbon additives to reach the performance targets in high performance concrete applications such as bridges, pavements and smart infrastructure. This research encourages sustainability through the reduced use of cement and reduction of industrial waste by using waste derived carbon materials.

Keywords: Carbon-based nanomaterials, Nano-carbon additives, Static modulus, Dynamic modulus, Concrete.

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1. INTRODUCTION

The use of carbon based nano-materials to enhance functionality and durability of cementitious composites has shown much promise. Concrete that includes some of these Nano materials like carbon powder and graphene, for example, becomes stronger mechanically and more electrically conductive as well as less susceptible to environmental decay [1, 2]. Wenner Resistivity is one among other assessment methods used to test the concrete electrical resistivity and study its durability and resistant to moisture and chloride ion penetration. A lower Wenner Resistivity means higher permeability, less likely to corrode reinforcing steel, an important load term for long-term structural performance [3, 4]. The carbon powder is the waste materials generated from aluminium, petroleum and agriculture industries. Due to very fine particles, once this waste polluted in water or soil, it will become very challenging to control the pollution resulting detrimental impacts to soil and water flora and fauna [5, 6].

The focus of this study is to examine the effects of adding of carbon powder (nanoparticles) as a replacement of cement in conventional concrete as well as determine its effects on static and dynamic modulus properties. The research seeks to establish correlation between carbon Nano-material inclusion in concrete and the respective change in the modulus. In this work, the effect of nano carbon powder as a part cement substitute in M20, M25 and M30 concretes grade analysed its effect on the modulus of static and dynamic properties. The novelty of this research involves:

1. Making a direct correspondence between nano-carbon inclusion and moduli variations.
2. Investigating the effects of optimum desired dosage i.e. 5 % on the stiffness and durability.
3. How to address the dispersion challenges of nano materials at higher replacement levels.

1.1 Importance of Static and Dynamic Modulus

The static modulus of elasticity (E_s) and the dynamic modulus of elasticity (E_k) are the most important characteristics to evaluate the concrete mechanical behaviour under static and dynamic loadings. Static modulus is a stiffness and elastic response under a sustained loading, which affect the crack resistance and structural stability. Dynamic modulus, however, use to assess material response to cyclic and vibrational loading and provides an important long-term performance and fatigue resistance characteristic. The moduli that depend on various factors, such as cement type, aggregate type, aggregate grading, etc. These changes used to predict how long a concrete structure would last. Development of durable and resilent concrete members requires in-depth study related modulus properties [7, 8].

Dynamic modulus of concrete in this study observed using direct ultrasonic pulse velocity and density values. The relationship described in equation 1 for one-

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dimensional members such as cylinders. This relationship obtained using vibration theory in elastic materials described in Lee et al. (2017) [9].

$$V_p = \sqrt{D_e/\rho}, \qquad (1)$$

where, V_p stands for one-dimensional longitudinal pulse velocity (km/sec); D_e represents dynamic modulus (GPa); ρ represents the density of the specimen (kg/m^3); and v represents Poisson ratio. In this study, equation (1) applied to obtain dynamic modulus, because the concrete cylindrical specimen represents a finite one-dimensional element described.

1.2 Latest Advancements in Nano-Carbon Applications

The application of nano-carbon in cementitious composites explored in the application of improving the mechanical and durability properties. Jiang et al. (2024) pointed out that carbon nanomaterials enhance self-sensing in the structural health monitoring. It is similar to waste-based nano materials for sustainable construction as noted by Ahmad et al. (2021). They (Gou et al., 2019) also studied the uses of tailings in cement and concrete, suggesting a possible material reusability path.

Based on the findings obtained from this study, this research attempts to expand beyond these findings to examine the impact of nano carbon enhancement on structural performance in terms of both static and dynamic modulus variations. The work presented outlines a method for developing cementitious materials with improved mechanical efficiency and sustainability by combining recent advances of nano-carbon research.

2. MATERIALS AND METHODS

2.1 Materials Used

In this study, Ordinary Portland Cement (OPC 43 grade), fine aggregates (zone 3 sand) and coarse aggregates (20 mm downsize crushed stones) have been used as materials. The details of the material properties for casting specimens described in Table 1. BIS 2386-1, 2386-3, 2386-4 (1963 R-2016) codes were used to obtain different material properties. [10-16].

Table 1 – Material properties

Concrete Ingredients	Specific Gravity	Water Absorption (%)	Finesse Modulus	Crushing Value
Cement	3.08	n.a.	n.a.	n.a.
Sand	2.66	2.82	3.05	n.a.
Stone (NSA)	2.55	3.05	8.21	12.45

2.2 Mix Design & Specimen Preparation

M20, M25, and M30 grade concrete were cast incorporating Nano carbon powder as cement substitute. Nano carbon powder has introduced as a partial cement replacement at the levels of 5 %, 10 % and 15 %. First blending the dry ingredients (carbon powder, cement, sand and stone chips) uniformly, and then adding the water gradually using mixer machine. Cylindrical specimens with size 100 mm dia. and 200 mm length were prepared. Total 108 no. of specimens were prepared using different carbon percentages, described in Table 2. After proper curing (i.e. 14, 28, and 84 days), presented in Figure 1(a) the specimens were tested using ultrasonic pulse velocity test presented in Figure 1(a) for finding dynamic modulus. The compression-testing machine attached with dial gauge used for finding static modulus, presented in Figure 1 (b). The preparation of this method allowed a controlled study of the influence of Nano carbon powder in concrete static and dynamic modulus properties.

Fig. 1 – (a) Cylindrical sample curing, compression testing and (b) ultrasonic pulse velocity test

The details of the specimen classification provided in Table 2.

Table 2 – Classification of sample

Sample Description	Age (Days)	Carbon replacement (%)			
		0	5	10	15
M20	14	3 no	3 no	3 no	3 no
	28	3 no	3 no	3 no	3 no
	84	3 no	3 no	3 no	3 no
M25	14	3 no	3 no	3 no	3 no
	28	3 no	3 no	3 no	3 no
	84	3 no	3 no	3 no	3 no
M30	14	3 no	3 no	3 no	3 no
	28	3 no	3 no	3 no	3 no
	84	3 no	3 no	3 no	3no

3. RESULTS AND DISCUSSION

3.1 Impact of Age, Grade and Carbon Powder on Static Modulus

Figures 2(a), 2(b), and 2(c) represent the static modulus with age for M20, M25 and M30 grade concrete respectively. The static modulus increases for every grade specimens with age significantly upto 5% carbon powder replacement. At higher replacement percentages (5 %, 10 %, and 15 %), the rate of increment decreases. This observed due to lesser C-S-H gel formation in concrete. The static modulus increases up to 5 % replacement due to optimum amount of C-S-H gel formations and finer carbon particles resulting denser concrete with lesser voids and porosity.

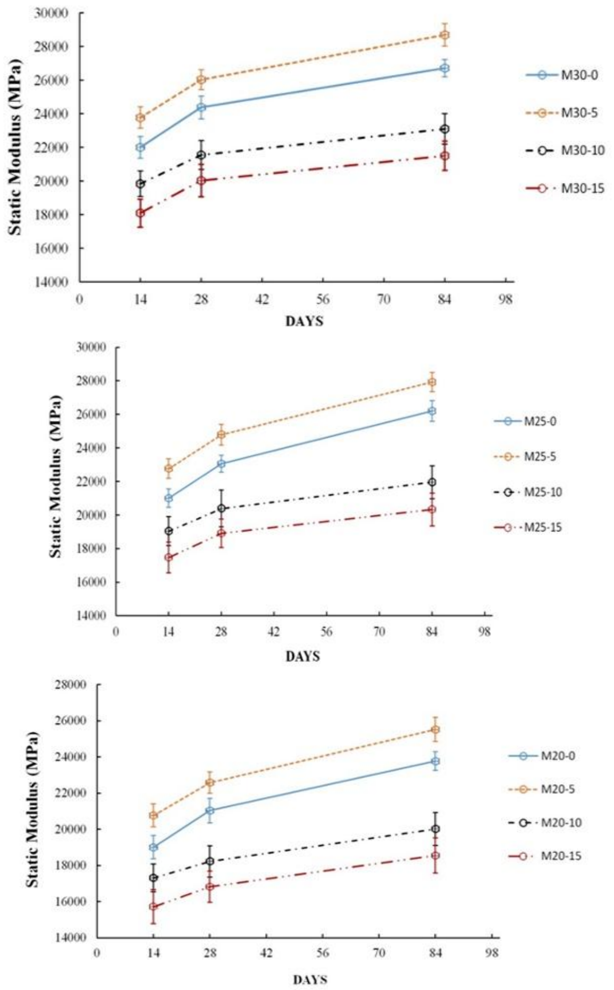
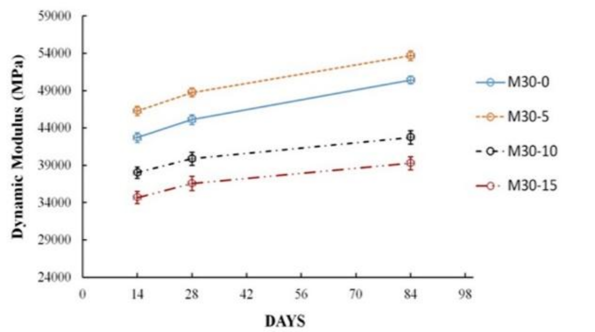


Fig. 2 – Static Modulus test (a) M20; (b) M25; and (c) M30 grade

Figures 3(a), 3(b), and 3(c) shows the dynamic modulus for M20, M25 and M30 grade concrete respectively. Similar, kind of conclusions obtained from static modulus observed for dynamic modulus of concrete specimens. Dynamic modulus results obtained using ultrasonic pulse velocity and density results described in equation (1).



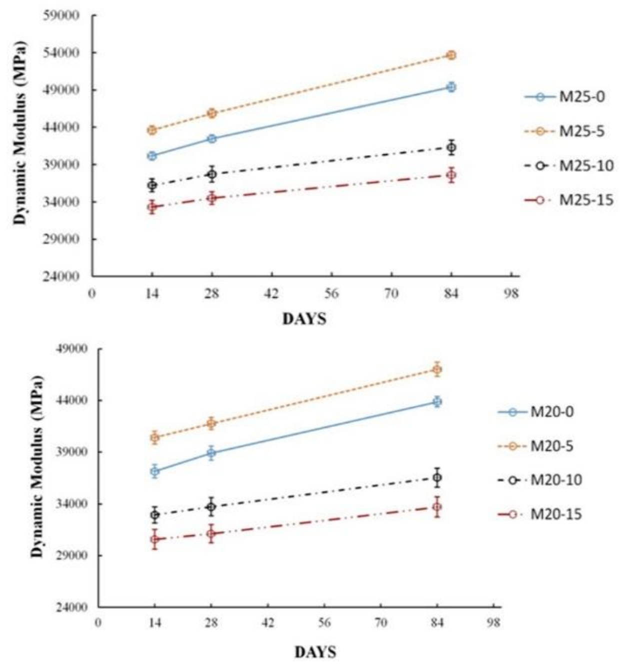


Fig. 3 – Dynamic Modulus test (a) M20; (b) M25; and (c) M30 grade

Table 3 describe the static and dynamic modulus values for each type of specimens with their corresponding standard deviation observed from mean. From test results, it can observe that uncertainity (standard deviation from mean) increases with higher replacement percentages (i.e. 10 and 15%). This is due to lesser C-S-H gel formation and higher carbon particles in the specimen.

Table 3 – Specimen details with test values

Description (Grade/Age/Carbon %)	Mean Static Modulus (MPa)	Standard Deviation (MPa)	Mean Dynamic Modulus (MPa)	Standard Deviation (MPa)
m20-14-0%	19006.15	642.48	37161.37	873.78
m20-14-5%	20766.61	633.66	40418.23	861.77
m20-14-10%	17316.50	878.97	32935.53	1195.40
m20-14-15%	15714.89	941.44	30572.54	1280.35
m20-28-0%	21036.64	677.13	38917.78	920.90
m20-28-5%	22581.28	587.67	41775.37	799.23
m20-28-10%	18232.32	843.02	33729.80	1146.51
m20-28-15%	16820.31	868.70	31117.58	1181.44
m20-84-0%	23770.01	510.89	43874.52	694.81
m20-84-5%	25521.67	663.89	47015.09	902.90
m20-84-10%	20025.89	987.06	36547.90	1342.40
m20-84-15%	18547.15	971.45	33712.24	1321.17
m25-14-0%	21002.89	551.48	40155.35	750.01
m25-14-5%	22765.29	581.14	43615.80	790.35
m25-14-10%	19038.63	859.62	36221.47	1169.09

m25-14-15%	17466.52	910.96	33313.07	1238.90
m25-28-0%	23057.85	501.86	42457.01	682.53
m25-28-5%	24793.20	615.86	45867.41	837.56
m25-28-10%	20391.55	1087.03	37724.36	1478.36
m25-28-15%	18912.24	838.99	34487.64	1141.03
m25-84-0%	26205.65	622.05	49380.45	845.98
m25-84-5%	27928.58	562.42	53667.88	764.89
m25-84-10%	21955.39	980.21	41317.46	1333.08
m25-84-15%	20327.36	981.93	37605.61	1335.42
m30-14-0%	22006.07	577.65	42711.24	785.61
m30-14-5%	23775.68	245.10	46285.00	333.34
m30-14-10%	19846.14	765.71	38015.35	1041.36
m30-14-15%	18093.72	824.51	34673.38	1121.34
m30-28-0%	24381.36	606.17	45105.51	824.39
m30-28-5%	26026.42	642.31	48748.87	873.54
m30-28-10%	21551.24	861.29	39869.79	1171.36
m30-28-15%	20032.86	962.10	36560.79	1308.45
m30-84-0%	26713.88	365.05	50420.68	496.47
m30-84-5%	28694.68	420.41	53685.15	571.76
m30-84-10%	23103.91	907.57	42742.23	1234.30
m30-84-15%	21506.62	869.88	39287.25	1183.03

4. CONCLUSION

This research shows the application of carbon based nano materials as a cement replacement in conventional concrete, and its effect in static and dynamic modulus of the concrete. The results obtained in the experiments confirm that increase in the carbon powder content have a positive effect on both static and dynamic modulus of concrete up to 5 %. The increases in static modulus observed by 8.23 %, 7.57 %, and 7.31 % for M20, M25, and M30 grade concrete respectively. Similarly, increase in dynamic modulus observed by 0.8 %, 1.37 %, and 1.19 % for M20, M25, and M30 grade concrete respectively.

- The study also observes that the increment in both modulus rate with age of curing decreases at higher replacement percentages for every grade of concrete. This due to incorporating higher carbon particles resulting lesser C-S-H gel formation from cement hydration.
- The study also observe that at higher replacement of carbon powder, uncertainty (standard deviation from mean) for both static and dynamic modulus increases. This observed due to higher porosity and material non-uniformity from lesser C-S-H gel productions.

This study provides valuable insights for specimen using carbon powder and it effect in concrete static and dynamic modulus. It can conclude that using higher carbon powder will be beneficial for structural concrete upto 5% replacement. More in-depth studies incorporating microscopic analysis and consideration of different other properties conducted in future studies.

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Вплив нановуглецевих добавок на механічні властивості цементних композитів: дослідження змін статичних та динамічних модулів пружності

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Досліджено вплив нановуглецевих добавок на механічні характеристики та довговічність цементних композитів з точки зору статичного та динамічного модуля пружності. Порошок нановуглецю було додано в концентрації 5%, 10% та 15% як замінник цементу в бетонах марок М20, М25 та М30, а механічні властивості були визначені для віку твердіння 14, 28 та 84 днів. Ці результати показують, що додавання 5 % нановуглецю покращило статичний та динамічний модуль пружності, збільшуючи жорсткість, стійкість до втоми та несучу здатність. Однак значення модуля знизилися при рівнях заміни понад 10 % та 15 % (через ефекти агломерації та неоднорідне розсіювання частинок вуглецю в матрицях). Статистичний аналіз варіацій модуля показав меншу мінливість при 5 % заміні, що свідчить про хороші характеристики. Ці результати підтверджують, що при контрольованих дозах нановуглецеві добавки покращують механічні властивості та підходять для високоефективних бетонних мостів, дорожніх покриттів та інтелектуальної інфраструктури. Це дослідження підкреслює можливість використання нановуглецевих добавок для досягнення цільових показників у високоефективних бетонних застосуваннях, таких як мости, дорожні покриття та інтелектуальна інфраструктура. Це дослідження заохочує сталий розвиток шляхом зменшення використання цементу та зменшення промислових відходів завдяки використанню вуглецевих матеріалів, отриманих з відходів.

Ключові слова: Вуглецеві наноматеріали, Нановуглецеві добавки, Статичний модуль пружності, Динамічний модуль пружності, Бетон.