3rd Conference on Sustainability in Civil Engineering (CSCE'21)
Department of Civil Engineering
Capital University of Science and Technology, Islamabad Pakistan

EFFECT OF CARBON BLACK ON PROPERTIES OF STEEL FIBER-REINFORCED CONCRETE

[a] Abasal Hussain*, [b] Zahoor Hussain

a: Department of Civil and Environmental Engineering, The Hong Kong Polytechnic University, Kowloon, Hong Kong, China, abasal.hussain@connect.polyu.hk
b: Department of Civil Engineering, Zhengzhou University, Zhengzhou, Henan 450001, China, dutian17@outlook.com
* Corresponding author: Email ID: abasal.hussain@connect.polyu.hk

Abstract- In this research work, hybrid conductive materials like carbon nano black (CNB) and macro steel fiber (SF) are integrated into the cementitious composite to investigate the mechanical properties and self-sensing properties of the conductive concrete flexural members. For that purpose, 70 kg/m^3 steel fiber with three different dosages of carbon black is evaluated. The mechanical properties like compressive strength, flexural strength and toughness are evaluated. Furthermore, the relationship of fractional change in resistance (FCR) and crack opening displacement (COD) has been determined to study the effect of different types of conductive materials on the gauge factor. The results reveal that the mechanical properties (compression strength, toughness, and flexural strength) are improved with diphasic conductive admixture. Furthermore, the gauge factor is enhanced with the addition of CNB.

Keywords- Self-sensing concrete; steel fiber; carbon nano black; the fractional change in resistance.

1 Introduction

Concrete civil infrastructures throughout their service life are pregnable to different loadings, fatigue, erosion, or aging, which leads to the collapse of concrete infrastructures [1]. Therefore, the proper maintenance and monitoring system is required for long-term durability. Structural health monitoring (SHM) in civil infrastructure is an emerging technology in the past few decades. SHM of concrete structures is applied to give information about structural conditions regarding durability and contribute to the extent of their service life [2], [3]. For this purpose, different health monitoring systems are utilized in civil infrastructure. Different sensors are attached, which are expensive, short lifetime and all above incompatibility with concrete structure. Therefore, it is not the permanent and filed deployable solution for SHM.

These are some of the reasons which lead to the development of conductive concretes. The conductive (piezoresistive behaviour) concrete is fabricated by adding a different conductive fiber and fillers. Piezo resistivity can be described as the physical property of materials that changes electrical resistivity when the material is subjected to mechanical strain [5], [6]. The hybrid use of different conductive materials improves not only the conductive properties but also the mechanical properties of the cementitious matrix. For this purpose, micro and/or nano-scale fiber and conductive fillers are normally used to produce structural conductive concrete. Numerous types of conductive fillers have been explored i.e., carbon fibers[7]–[9], carbon nanotubes[10]–[12], steel fibers [13], [14], and carbon black [15]–[17].

Hybrid use of different conductive materials such as fiber and filler would be more effective for improving mechanical and electric conductivity of cementitious matrix by facilitating the conductive matrix and crack bridging by macro fibers. Steel fiber (SF), with its strong electric and mechanical properties, is an ideal material for concrete flexural members. In addition, it shows deflection-hardening behaviour relatively large energy absorption capacity by bridging the cracks with a considerable volume fraction of SF. On the other hand, carbon nano black (CNB) has high chemical and thermal stability, low cost, permanent electrically conductive properties, and a filling effect potentially be employed as ideal materials for the conductive behaviour of concrete.

2 Research significance

Carbon nano tubes and CF have also improved the conductive properties, but the unit cost of the materials is very high as compared to carbon black and they need very extensive dispersion techniques to ensure the proper dispersion. Therefore, this study investigates the carbon nano black with steel fiber to improve the mechanical properties and sensing behaviour of the concrete beam, which is a very cost-effective and field-deployable solution for structural health monitoring in civil infrastructure. The effect of steel fiber and carbon black on the energy absorption capacity of concrete beams is also investigated. Also, the correlation between crack opening displacement (COD) and the fractional change in electrical resistance (FCR) has been examined.

3 Experimental Procedure

3.1. Material properties and base mix design

The mix design of conductive concrete strength grade C30 was used to fabricate the conductive concrete. Ordinary Portland cement 42.5R, class F fly ash. The particle size of quartz sand is 0 ~ 5mm; coarse aggregate size is 5 ~ 10mm and a high-water reducing agent from Sika polycarboxylate superplasticizer (SP) is used.

Table 1-The dosage of conductive materials in a mix design (kg/m^3)

Mix ID	Steel Fibre (SF)	Carbon nano Black (CNB)
PC	-	-
SF70	70	-
SF70CNB2	70	02
SF70CNB4	70	04
SF70CNB6	70	06

SF and CNB stand for macro steel fiber and carbon nano black, respectively. The number shows the content of conductive materials in kg/m^3; For example, SF70CNB6 implies that the specimen with 70 kg/m^3 steel fibers and 6 kg/m^3 carbon nano black.

The conductive materials, carbon nano black (CNB) (Fig. 1(a)) having a particle size of 30-90 nm, a density of 0.5 g/cm^3 and the volumetric resistivity is 2.30 ohm-cm. The steel fibers (SF) (Fig. 1(b)) with a length of 35 mm and diameter of 0.55 mm are added. The density is about 7.85 g/cm^3 and aspect ratio of steel fiber is 65, and the volumetric resistivity is 10-5 Ω-cm. The dispersion of a nano carbon black is done by dry mixing cementitious materials and aggregated with CNB, which will help the carbon black to disperse at an accepted level. The second thing, SP is also helpful to disperse the carbon nano materials. Table 1 shows the specimens with different amounts of materials.

a) b)

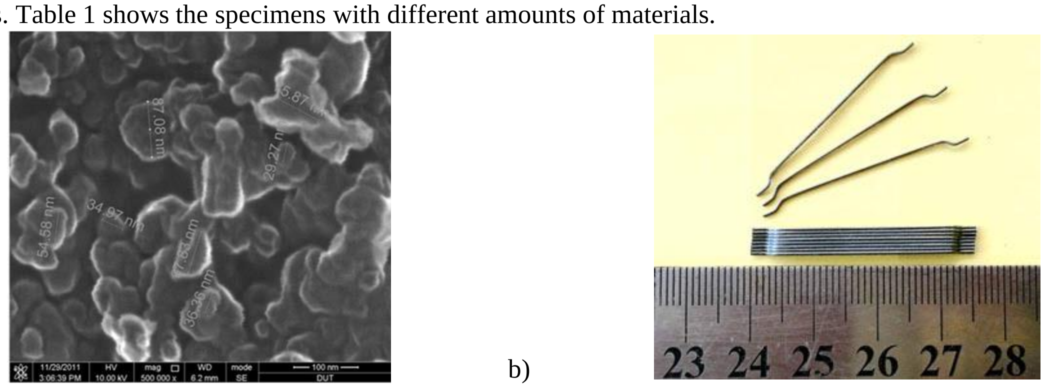

Fig. 1 (a) Show the average carbon nano black particle size by using SEM and (b) macro steel fiber.

3.2 Test methods

According to ASTM C1609, the flexural load is applied on fiber-reinforced concrete beam specimens of 400 x 100 x 100 mm under third-point loading using a closed-loop, servo-controlled testing system are evaluated [18]. According to the four-electrode electric resistance measurement system, four copper meshes are used as an electrode. The displacement rate is 0.2 mm/min at mid-span until the specified deflection is reached. One LVDT on the front and one on the rare side is used to measure the deflection of the mid-span. In addition, an extensometer is attached at the mid-span of the beam to measure the crack opening displacement during the test.

The following equation calculates FCR.

$$FCR = \frac{R - R_0}{R_0} \qquad (1)$$

R is representative of the resistance value at any point during the test, R_0 is the initial value of the resistance before the test and the unit of R and R_0 is Ω.

4 Experimental results and discussion

4.1 Effect of conductive material on workability

The Effect of carbon nano black and steel fiber on fresh properties are also investigated. The addition of conductive admixture has greatly reduced the workability of concrete. It is the nature of nano materials to absorb too much water due to nano size. The specific surface area of the nano materials is high, which would lead to adsorbed more free water and superplasticizer onto the surface of nanomaterials[19]. Therefore, it decreased free water content and thus decreased the workability of the mix and increased the water demand. In this investigation, the SF and CNB have greatly decreased, as shown in Table 2. With respect to plain concrete, the steel fiber 70 kg/m^3 has decreased up to 8% of the slump. But the CNB has decreased up 49% of the slump with 6kg/m^3.

4.2 Effect of conductive material on compressive strength

The CNB and carbon fiber increases the compressive strength (f_{cu}) with various dosages of materials, as described by Ding et al. [20]. It can be noticed that the compressive strength of specimens containing diphasic conductive materials (SF+CB) has improved up to 23.85% that of plain concrete (PC). The improvement of compressive strength by the addition of SF70 is 5.02% concerning PC, as shown in Table 2. In diphasic conductive mixes, the increment in compressive strength is linear with an increasing amount of CNB up to 6kg/m^3. With the addition of carbon nano black by 2, 4 and 6 kg/m^3 compressive strength is improved by 7.86%, 15.52% and 23.85%, respectively, compared to plain concrete. It can be explained that CNB shows its filler effect, which fills nano-level pores of the matrix. The more filled voids, the more dense and consolidated concrete, which ultimately increase compressive strength.

4.3 Effect of conductive materials on flexural strength

The flexural strength (f_P) of the specimen with carbon nano black and steel fiber conductive materials has been investigated through ASTM C1609. The comparison of f_P of the conductive concrete beams to PC is illustrated in Table 2.

It can be seen from the data in the table, the flexural strength of the conductive concrete beam with SF 70 kg/m^3 (SF70) is increased by 32.09 % as compared to plain concrete. The flexural strength of 70 kg/m^3 SF content with hybrid conductive admixture, SF70CNB2, SF70CNB4 and SF70CNB6 (beams with SF 70 kg/m^3 and CNB 2 - 6 kg/m^3) are increased by 72.73%, 78.76% and 86.24% respectively to PC. In hybrid conductive mixes of SF70, the 02 kg/m^3 CNB dosage doesn't improve well than 04 kg/m^3 and 06 kg/m^3. It can be attributed that a lower amount of CNB may not significantly affect the flexural strength performance of the beam, but, with 4 kg/m^3 and 6 kg/m^{3,} CNB content has dramatically improved the flexural strength. The reason behind this increment would be the nanopore filling effect of the CNB, which enhances the bond behaviour of steel fiber to the matrix.

Table 2-Details of the Compressive strength, Flexural strength, Toughness and FCR with different conductive materials

Specimen	**Compressive strength** f_{cu} **(N/mm²)**	**Flexural strength** f_P **(kN)**	**Toughness** T^D_{150} **(J)**	**FCR (%)**	**Slump (mm)**
PC	38.66	7.10	-	-	200
SF70	40.60	9.37	38.43	42.10	186
SF70CNB2	41.70	12.26	39.14	50.14	169
SF70CNB4	44.66	12.69	48.65	51.32	153
SF70CNB6	47.88	13.22	53.51	59.67	134

Where, FCR at COD =5.0mm

4.4 Effect of conductive materials on toughness

The experimental data evaluation of the toughness parameter (post crack energy absorption capacity) is carried out based on ASTM C1609. T^D_{150} is the toughness of the beam and is calculated by the area of the Load-displacement curve up to a net deflection of L/150 (2.0 mm), where L stands for the span length of the beam. Fig. 2 shows the Load-displacement diagram of PC, SF70 with 2-6 kg/m^3 CNB conductive materials. The T^D_{150} values of monophasic and diphasic conductive materials are shown in Table 2. It can be noticed that the PC flexural member does not demonstrate any flexural toughness because the PC beam does not have any fiber, so it shows strong brittle behaviour.

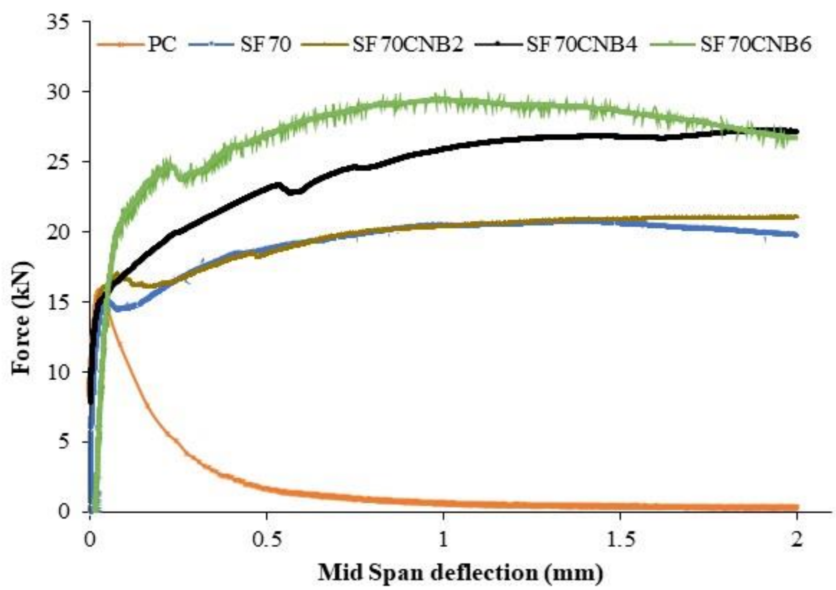

Fig. 2 The Load-displacement curve of solo and hybrid conductive materials and PC

Compared to the plain concrete beam, the addition of steel fiber has shown significant improvement in the toughness of the concrete beam. The toughness (T^D_{150}) of diphasic conductive materials specimens SF70CNB2, SF70CNB4 and SF70CNB6 toughness values are increased by 1.9%, 26.6% and 39.3%, respectively, concerning SF70. Therefore, it can be concluded that the CNB with 2-6 kg/m^3 shows a positive effect. The improvement in toughness can also be counter checked by compressive strength results that as the CNB increased, the compressive strength is also increased. So, the bond between the matrix and steel fiber is improved by the more compacted and consolidated matrix which will lead a higher energy absorption capacity.

4.5 Effect of hybrid conductive materials on FCR-COD

The effects of CNB and SF conductive materials on the relationships of the fractional change in resistance (FCR) and the crack opening displacement (COD) of concrete flexural members are demonstrated in Table 2. Generally, it is believed that above the percolation threshold of conductive material, the FCR values value does not show any noticeable improvement as the SF content increased. The percolation threshold is classified as the dosage of the conductive admixtures, where they make a conductive path to flow electric charges. Higher the FCR means higher the resistance change with the strain, which is the gauge factor. The gauge factor of SF 70 is 41.26 and the gauge factor of carbon black with 6 kg/m^3 59.67 at COD 5mm. The improvement in gauge factor is about 45% by the addition of 6 kg/m^3 due to the synergetic effect of both conductive materials. The conductive carbon nano black improves the conductivity of the matrix at the nano level. The SF 70 kg/m^3 provides a maximum number of fibers to bridge the cracks and the moments of the electrons are more stable and resilient. The diphasic conductive phase SF70CNB2, SF70CNB4 and SF70CNB6, have higher FCR values than solo SF 70 by 19.1%, 21.9% and 30.8%, respectively. PC does not show any FCR because it is a pure insulator with no conductive admixture. The FCR-COD is improved with the addition of CNB. The FCR values are increased by the addition of steel fiber with 70 kg/m^3. Moreover, the addition of CNB has further improved the FCR by 45% concerning solo use of SF. It means that the carbon nano black has a clear effect on the conductivity of the member, which will lead the higher sensitivity for the crack of the member. The CNB with 6 kg/m^3 have the higher FCR values which could be attributed that the higher amount of the CB has a permanent and strong conductive path by tunnelling effect of the CNB particles, so the change in resistivity with initiation of the crack is higher.

This work is a to study for the self-sensing and self-diagnosing of single and multiple cracking behavior of concrete flexural members. The hybrid use of the nano carbon black and steel fiber is beneficial for both mechanical and self-sensing properties of concrete beam. It will be a very cost-effective field deployable solution. It would replace the very expensive and complicated structural health monitoring techniques.

5 Conclusion

This study investigates the use of carbon nano black (CNB) and macro-steel fiber (SF) as a hybrid electric conductive material for the self-sensing ability of the beam. A series the experimental and analytical investigations, the results lead to the conclusions as follows:

1. The fresh properties like workability have decreased nut the combined use of macro-SF and CNB has shown an improvement in compressive strength, and flexural strength up to 23.85% and 86.24%, respectively, with respect to PC.
2. The compressive strength and flexural strength of 2 to 6 kg/m^3 CNB show a clear improvement of 17.93% and 41.00 %, respectively, concerning SF 70 kg/m^3.
3. The toughness of hybrid uses of the SF and CNB compared to solo use of steel fiber is improved by 39.3%, respectively.
4. The gauge factor of the conductive admixture is highly improved by adding carbon nano black up to 6 kg/m^3 by 45% compared to solo use of SF.

Recommendation

The followings are some recommendations for future studies

1. The dispersion of the carbon black is not studied properly. It is recommended an extensive investigation on carbon black dispersion is needed.
2. Durability parameters of the carbon black incorporated concrete are recommended to investigate further.

Acknowledgement

The authors would like to thank all the people/organizations who helped throughout the research.

References

[1] J. Ou, "Research and practice of intelligent sensing technologies in civil structural health monitoring in the mainland of China," *Nondestruct. Eval. Heal. Monit. Aerosp. Mater. Compos. Civ. Infrastruct. V*, vol. 6176, p. 61761D, 2006, doi: 10.1117/12.663993.

[2] G. Song, Y. L. Mo, K. Otero, and H. Gu, "Health monitoring and rehabilitation of a concrete structure using intelligent materials," *Smart Mater. Struct.*, vol. 15, no. 2, pp. 309–314, 2006, doi: 10.1088/0964-1726/15/2/010.

[3] H. N. Li, D. S. Li, and G. B. Song, "Recent applications of fiber optic sensors to health monitoring in civil engineering," *Eng. Struct.*, vol. 26, no. 11, pp. 1647–1657, 2004, doi: 10.1016/j.engstruct.2004.05.018.

[4] B. Han and J. Ou, "Embedded piezoresistive cement-based stress/strain sensor," *Sensors Actuators, A Phys.*, vol. 138, no. 2, pp. 294–298, 2007, doi: 10.1016/j.sna.2007.05.011.

[5] A. O. Monteiro, P. B. Cachim, and P. M. F. J. Costa, "Self-sensing piezoresistive cement composite loaded with carbon black particles," *Cem. Concr. Compos.*, vol. 81, pp. 59–65, 2017, doi: 10.1016/j.cemconcomp.2017.04.009.

[6] S. Wen and D. D. L. Chung, "Effect of moisture on piezoresistivity of carbon fiber-reinforced cement paste," *ACI Mater. J.*, vol. 105, no. 3, pp. 274–280, 2008.

[7] A. Dehghani and F. Aslani, "Piezoresistive sensing of cementitious composites reinforced with shape memory alloy, steel, and carbon fibres," *Constr. Build. Mater.*, vol. 267, no. xxxx, 2021, doi: 10.1016/j.conbuildmat.2020.121046.

[8] L. Wang and F. Aslani, "Mechanical properties, electrical resistivity and piezoresistivity of carbon fibre-based self-sensing cementitious composites," *Ceram. Int.*, vol. 47, no. 6, pp. 7864–7879, 2021, doi: 10.1016/j.ceramint.2020.11.133.

[9] Z. Zhou *et al.*, "Electrical properties of low dosage carbon nanofiber/cement composite: Percolation behavior and polarization effect," *Cem. Concr. Compos.*, vol. 109, no. January, 2020, doi: 10.1016/j.cemconcomp.2020.103539.

[10] M. S. Konsta-Gdoutos *et al.*, "Effect of CNT and CNF loading and count on the corrosion resistance, conductivity and mechanical properties of nanomodified OPC mortars," *Constr. Build. Mater.*, vol. 147, pp. 48–57, 2017, doi: 10.1016/j.conbuildmat.2017.04.112.

[11] F. Azhari and N. Banthia, "Cement-based sensors with carbon fibers and carbon nanotubes for piezoresistive sensing," *Cem. Concr. Compos.*, vol. 34, no. 7, pp. 866–873, 2012, doi: 10.1016/j.cemconcomp.2012.04.007.

[12] A. Naqi, N. Abbas, N. Zahra, A. Hussain, and S. Q. Shabbir, "Effect of multi-walled carbon nanotubes (MWCNTs) on the strength development of cementitious materials," *J. Mater. Res. Technol.*, vol. 8, no. 1, pp. 1203–1211, 2019, doi: 10.1016/j.jmrt.2018.09.006.

[13] Y. Ding, G. Liu, A. Hussain, F. Pacheco-Torgal, and Y. Zhang, "Effect of steel fiber and carbon black on the self-sensing ability of concrete cracks under bending," *Constr. Build. Mater.*, vol. 207, pp. 630–639, 2019, doi: 10.1016/j.conbuildmat.2019.02.160.

[14] L. Shi, Y. Lu, and Y. Bai, "Mechanical and Electrical Characterisation of Steel Fiber and Carbon Black Engineered Cementitious Composites," *Procedia Eng.*, vol. 188, pp. 325–332, 2017, doi: 10.1016/j.proeng.2017.04.491.

[15] A. Hussain, Y. Ding, G. Liu, and A. Naqi, "Study on self-monitoring of multiple cracked concrete beams with multiphase conductive materials subjected to bending," *Smart Mater. Struct.*, vol. 28, no. 9, 2019, doi: 10.1088/1361-665X/ab2cfe.

[16] A. O. Monteiro, P. B. Cachim, and P. M. F. J. Costa, "Electrical Properties of Cement-based Composites Containing Carbon Black Particles," *Mater. Today Proc.*, vol. 2, no. 1, pp. 193–199, 2015, doi: 10.1016/j.matpr.2015.04.021.

[17] A. O. Monteiro, A. Loredo, P. M. F. J. Costa, M. Oeser, and P. B. Cachim, "A pressure-sensitive carbon black cement composite for traffic monitoring," *Constr. Build. Mater.*, vol. 154, pp. 1079–1086, 2017, doi: 10.1016/j.conbuildmat.2017.08.053.

[18] C. C. Test, T. Drilled, C. Concrete, and S. T. Panels, "C 1609/C 1609M-05 Standard Test Method for Flexural Performance of Fiber-Reinforced Concrete (Using Beam With Third-Point Loading) 1," *Astm*, vol. i, no. C 1609/C 1609M-05, pp. 1–8, 2005, doi: 10.1520/C1609.

[19] Z. Wu, C. Shi, K. H. Khayat, and S. Wan, "Effects of different nanomaterials on hardening and performance of ultra-high strength concrete (UHSC)," *Cem. Concr. Compos.*, vol. 70, pp. 24–34, 2016, doi: 10.1016/j.cemconcomp.2016.03.003.

[20] Y. Ding, Z. Han, Y. Zhang, and J. B. Aguiar, "Concrete with triphasic conductive materials for self-monitoring of cracking development subjected to flexure," *Compos. Struct.*, vol. 138, pp. 184–191, 2016, doi: 10.1016/j.compstruct.2015.11.051.