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Effect of CFRP Strengthening Configuration and Steel Fiber on the Torsional Performance of Deep Beams under Repeated Pure Torsion

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ABSTRACT

This study aims to investigate the torsional behaviour of reinforced concrete deep beams enhanced with various CFRP configurations and steel fibres, subjected to repeated pure torsional loads. Five beams were constructed using normal-strength concrete. One specimen was internally reinforced with 1% steel fibres, while the others were externally strengthened with CFRP sheets in different configurations. The tested specimens included a control beam without strengthening, a beam with longitudinal CFRP sheets, a beam wrapped with CFRP strips, a beam with only steel fibres, and a combined beam utilizing both CFRP and steel fibres as a combined strengthening method. The experimental results demonstrated significant improvements in the ultimate torque capacity of all strengthened beams relative to the control specimen. The ultimate torque increased by 30.8% in the longitudinal CFRP specimen, 46.2% in the wrapped CFRP specimen, 37.7% in the steel fibre specimen, and 43.7% in the combined strengthening specimen. The wrapped CFRP configuration exhibited the greatest enhancement. Furthermore, all strengthened beams showed improved crack control, higher torsional stiffness, and enhanced ductility under repeated pure torsional loading.

1. Introduction

A Deep beam is a structural element with a significant depth compared to its span length and a relatively small width. Reinforced concrete deep beams are prevalent and significant components of large structures and superstructures, such as bridges, offshore constructions, and large multistory buildings. Its main purpose is to transmit loads such as foundations, transfer girders, pile caps, bent caps, and some walls. The ACI 318-19 [1] code defines a deep beam as a structural element that is loaded on one face and supported on the other face; a strut compression element can be set up between the load and the support, and that satisfy (1) or (2): (1) The clear span must not exceed four times the total member depth (h). (2) Concentrated loads are existent within a distance of 2h from the support face. Repeated loads, which occur in most actual event structures, can affect the size of the load factor at collapse. Two main classes of cyclic loading occur. One type of loading history shows substantial variations in bond stress during a short period of time (less than 100 cycles), and this is called low-cycle loading. Low cycle loading may be the consequence of strong seismic activity and wind loads. High cycle or fatigue loading is the second type of loading, and it includes many cycles with low bond stress levels— often hundreds or millions. Significant cyclic or fatigue load is often experienced by elements supporting vibrating machinery and bridge elements in offshore constructions [2].

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Externally bonded fiber-reinforced polymer (FRP) sheets are a novel strengthening technique used in concrete buildings. FRP has high strength, low weight, chemical resistance, fatigue strength, corrosion resistance, and the ability to form intricate shapes. Researchers from Japan, the US, and Switzerland investigated using CFRP wrapping methods to strengthen concrete bridge columns against seismic collapse. Notwithstanding the material's relatively high cost, the installation process allows substantial savings in labor and equipment expenses compared to traditional strengthening techniques. A cost evaluation of bridge strengthening using steel plates against CFRP plates indicated that CFRP strengthening provided a 17.5 percent decrease in cost [3-5].

In [6], the authors investigated the performance of reinforced concrete deep beams with openings reinforced by CFRP strips. Eight specimens were evaluated, comprising two control specimens and six specimens enhanced with CFRP strips in diverse configurations. The results showed that the strongest improvement in ultimate load (118.6%) was for specimens that had CFRP strips added both horizontally and diagonally, using square plates and a bolt to attach the strips to the top of the beam.

in [7] The research investigated the shear performance of self-compacting concrete deep beams reinforced with carbon fiber-reinforced polymer sheets. Eleven specimens were tested, of which 10 were strengthened with CFRP sheets. The strengthening method altered variables such as the number of sides, orientation angles, and the clearances between sheets. The results indicated an increase in cracking and ultimate loads for beams with a 20mm spacing between sheets, exhibiting a 27.3% and 24.8% enhancement in strength relative to the control beam.

Authors in [8] investigated the efficacy of carbon fiber-reinforced polymers in improving concrete specimens in this investigation. the shear strength of deep beams. The authors evaluated eight specimens and categorized them into four groups based on the presence of stirrups, CFRP sheets, and longitudinal bars. The first group didn't have stirrups, CFRP sheets, and longitudinal bars. The second group included stirrups and longitudinal bars, but without CFRP sheets. The third group utilized CFRP sheets positioned at 45º angles on both faces of the beam. The fourth group utilized CFRP sheets positioned at 90-degree angles. The application of CFRP sheets resulted in a 37% increase in ultimate load at a 45º angle and a 32% increase at a 90º angle.

However, previous studies have rarely addressed the torsional behavior of deep beams under repeated pure torsion. The interaction between different strengthening methods, especially CFRP sheets and steel fibers, remains insufficiently explored. This study aims to experimentally evaluate and compare strengthening techniques to identify the most effective in enhancing torsional capacity, cracking behavior, and ductility.

2. Experimental program

2.1 Normal strength concrete (NSC)

The materials' properties have been carefully evaluated using standardized testing procedures in accordance with Iraqi Standard (IQS) and ASTM standards. This study investigated a Type I common Portland cement, which was maintained in a dry state to protect it against various weather conditions. The test results revealed that the cement complied with Iraqi Standards (No. 5/1984) [9] and ASTM C150-17 [10]. Natural sand with the maximum particle size of 4.75 mm was utilized as the fine aggregate in concrete mixes for all construction types following the requisite evaluation. The graded fine aggregate satisfied the zone standards of IQS No. 45/1984 and ASTM C12815. The mixing and curing of all components were done using tap water.

Before mixing the NSC, it was essential to verify that the mixer was clean but not wet. The procedure started with the addition of gravel and sand into the mixer. One-third of the total water was used to hydrate the components for 60 seconds.

Thereafter, the cement was added and mixed for 30 seconds. Subsequently, an additional third of the water was included and blended for one minute. The residual water was gradually integrated and mixed for an additional minute, ending in a total mixing time of 1.5 minutes. The concrete mix has steel fiber that was introduced during the dry mixing stage, prior to the addition of water or admixtures. This sequence is essential to ensure a homogeneous distribution of the fibers within the dry matrix, avoiding fiber clumping and enhancing the bonding between fibers and the cement paste. The weight of content per cubic meter is shown in Table 1. The symbols F0 and F1 refer to the volume fractions of steel fiber of 0% and 1%, respectively.

2.2 REINFORCEMENT BARS

This study used two different sizes of steel bar reinforcement, as shown in Table 2. The test results of the steel bars conformed to the specification and satisfied the requirements of ASTM A496-97ae1 [11].

2.3 Steel Fiber

In this study, 30 mm long discrete steel fibers with hooked ends were used at 1.0% by volume. Table 3 shows the fiber properties as per the catalog. This ratio was chosen as it offers balanced torsional improvement; higher contents add little benefit, and lower ratios show limited effect.

Table 1: Weight of contents per cubic meter

Mix Type	Cement kg	Gravel kg	Sand kg	w/c	Fiber kg
NSC F0 NSC F1	300	1050	600	0.50	0 78

Table 2: Steel Bars Properties

Nominal Diameter mm	Actual Diameter mm	Yield Stress fy MPa	Ultimate strength, fu (MPa)	Elongation%	Modulus of Elasticity (GPa)	Min limit of Elongation %
10	9.8	495	708	15	200	9
12	11.9	560	715	14	200	9

Table 3: Steel fiber properties

Density	Average length (L)	Nominal diameter	Aspect ratio (L/D)	Poisson's ratio	Modulus of elasticity	Ultimate strength	Configuration
7800 kg/m3	30 mm	0.6 mm	50	0.24	200×103 MPa	1100 MPa	Hooked ends

3. Test Specimens

The study consists of five 1200 mm long RC deep beams with a 200 mm × 400 mm rectangular cross section. A clear span of 1000 mm was tested. The examined deep beams were fortified with two Φ12 bars as tension reinforcement and two Φ12 bars as compression reinforcement, respectively. The beams were vertically reinforced with double-legged steel stirrups of a 10 mm diameter at 150 mm intervals, and two stirrups with a conventional

diameter of 12 mm was installed horizontally. The clear cover for both the top and bottom reinforcement is 30 mm. Figures 1and 2 illustrates the dimensions and reinforcement details of the RC deep beam. The samples have been named as described in Table 4.

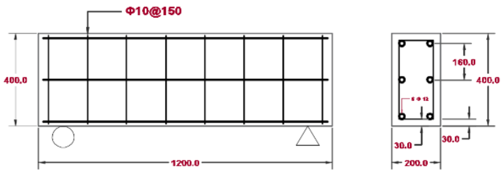

Figure 1. Reinforcing details and dimensions patterns of all Deep beam Specimen

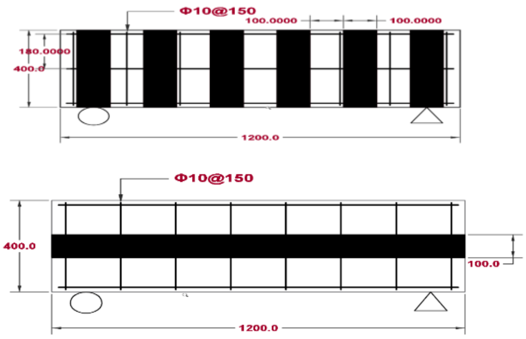

Figure 2. Details of the Tested Beam strengthened by sheet carbon

4. Strengthening Procedure of the Test Specimens

The first step in the process of strengthening beams was to prepare the surface of the concrete to the desired stage. This was done by first smoothing the surface using the appropriate sandpapers, then cleaning, drying, and removing any dust that was present. When the surfaces of the beams were prepared, both components of epoxy resin were mixed together (one part hardener to four parts resin) and used in a homogeneously mixed manner and immediately placed on the surface. This was done in accordance with the directions that were provided by the manufacturer. Afterwards, the CFRP sheets were affixed to the surface using sufficient power of hand to pack the epoxy into the CFRP and remove any air spaces that were present. After that, the surplus epoxy was immediately on the surface of the CFRP to ensure a strong connection and complete coverage. The bonding of one layer of CFRP-wrapped sheets was done by the use of the same technique.

5. Test Set Up

The test was carried out to focus the pure torsional effect on the five samples of the system hydraulic machine type EPP 300, where the device releases vertical force with a maximal 3000 kN.m capacity, in which vertical forces are converted into torsional torques, where steel and two steel arms. Before testing, the beam specimens were carefully prepared, ensuring that the applied load, locations of the supports, and dial gauges were precisely noted. The reference beam specimen (CRS0.re) was tested under monotonic loads in incremental steps until failure occurred. The other beam specimen was tested under repeated loading with five cycles. The cycles of the repeated loading reached the required amplitude and then returned to the zero level. The torque range for all specimens was set using a reference beam, with 60% as the upper limit of cyclic loading applied to both strengthened and unstrengthened specimens. If the beam specimen does not fail within the specified five cycles, the load continues to increase until failure.

Table 4: Specimens detail

named of Specimens	Details
CRS0	Conventional concrete, reinforced by Steel bars without strengthening
CRSCL	Conventional concrete, reinforced by steel bars, strengthened with sheet carbon on the length span.
CRSCW	Conventional concrete, reinforced by steel bars, strengthened with sheet carbon warping.
CRSF	Conventional concrete, reinforcement by steel bars, strengthened with steel fibre.
CRSCLF	Conventional concrete, reinforced by steel bars, strengthened with a sheet carbon on the length span and steel fibre

6. Control specimen testing

Tested the specimens using a universal compression machine with a capacity of 3000 kn. We use an average of three specimens for all mixes. The specifications of the control specimens are shown in Table 5.

Table 5: The specification of the control samples

Test classification	Quantity and shape of specimens	Specimen's dimensions (mm)	Average estimated value
Compression [12]	3 cubes	100×100×100	25 MPa
Modulus of rupture [13]	3 prisms	100×100×500	3.8 MPa
Splitting tensile strength [14]	3 cylinders	100×200	2.9 MPa
Modulus of elasticity [15]	3 cylinders	150×300	24.5 GPa

7. Results and discussion

7.1 Cracking Pattern and Mode of Failure

All of the specimens that were analyzed had their crack patterns photographed and displayed in Figure 3. The CRSCL specimen showed a delayed first cracking and moderate crack widths, approximately 0.2 mm and 0.75 mm. The cracks were uniformly distributed, indicating enhanced confinement and stress absorption. The CRSCW specimen exhibited lower cracking widths (about 0.15 mm to 0.33 mm) and a more uniform distribution of cracks over the beam surface. This wrapping approach improved the confinement over every perimeter of the section, resulting in increased resistance to cracking and more effective control over crack propagation. Warping wraps seem to surpass longitudinal strips in reducing cracking development because of the multi-directional confinement they offer. At the ultimate torsional load, interlaminar debonding was observed between the overlapping area of CFRP sheets at the top edge; only two CFRP sheets while all others remained intact strongly as shown in figure (4). The specimen (CRSF) exhibited delayed cracking and a more dispersed crack pattern on the surface, with significantly reduced crack widths (maximum 0.6 mm). This shows the ability of steel fibers to regulate the width of cracks and slow crack development by bridging micro-cracks and distributing stresses more uniformly. The combined strengthening models exhibited enhanced cracking behavior under pure torsion relative to singly strengthened or unstrengthened beams. In CRSCLF, show restricted crack width and limited their propagation, resulting in fine, short cracks uniformly dispersed over the surface.

Figure 3. Failure modes and cracking patterns of all Deep beam Specimen

Figure 4. Specimen (CRSCW)

7.2 Ultimate torsion Capacity

Figure 5 shows in the combined strengthening configuration (CRSCLF), where the specimen was strengthened with both longitudinal CFRP sheets and 1.0% steel fibres, a significant enhancement in torsional performance was observed. The first torsional crack (Tcr) appeared at 28.60 kN.m, whereas the ultimate torsional strength (Tu) reached 35.48 kN.m. In comparison to the specimen strengthened only with steel fibres (CRSF), which showed a Tcr of 25.80 kN.m and a Tu of 33.97 kN.m, the combined method resulted in a 10.9% enhancement in Tcr and a 4.4% improvement in Tu. In comparison to the CFRP-only specimen (CRSCL), which exhibited a Tcr of 24.73 kN.m and a Tu of 32.25 kN.m, the increases in the combined method were 15.7% for Tcr and 10.0% for Tu. The improvements indicate the multiplied effect resulting from the which provides surface confinement and restricts torsional deformations. Compared to the unstrengthened control specimen (CRS0), the combined system showed a significant enhancement of 66.3% in Tcr and 43.5% in Tu. This finding confirms that the combination of internal and exterior strengthening techniques significantly enhances both the pre-cracking stiffness and the post-cracking torsional resistance of deep beams.

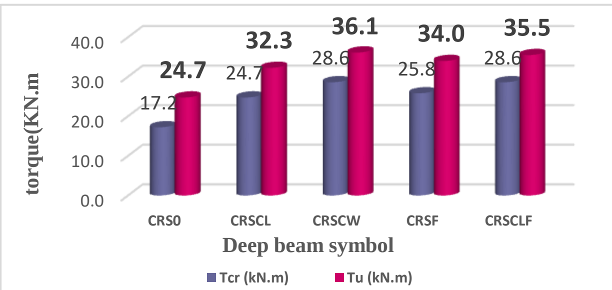

Figure 5. Cracking and Ultimate torque

7.3 Angles of twisting and elongation

Figure 6 shows the addition of 1% steel fibres in CRSF reduced residual deformation by around 32% compared to CRS0. Both CRSCL and CRSCW configurations significantly reduced residual angle of twist by 45.7% in CRSCL and 51.4%. In the comparison between CRSCL and CRSCW, the CRSCW specimen showed a 10.5% reduction in residual twist, improving load distribution, reducing localized stiffness degradation post-cracking, and resulting in a more stable and gradual torsional response. The CRSCLF specimen showed a 59.9% decrease in residual twist compared to CRS0, confirming the effectiveness of the integrated strengthening method in improving deformation control. It also showed a 26.3% decrease and 23.5% reduction in residual twist compared to CRSCL and CRSF, demonstrating a more stable post-cracking response due to the synergistic effects of fibres and CFRP confinement in stress distribution and the reduction of stiffness degradation. integration of steel fibres enhancing internal crack bridging and energy dissipation with the external CFRP sheet.

In the first four loading cycles, all specimens exhibited an approximately linear relationship between torque and longitudinal elongation, with no visible cracks recorded. CRSCL decreased elongation and residual by 25% and 30% relative to CRS0, but CRSCW achieved additional reductions of 45% and 50%, respectively. Both specimens exhibited linear behavior before the first cracking. CRSCW showed a more gradual nonlinear transition after cracking. The transverse CFRP wrapping in CRSCW exhibited improved confinement and crack distribution, rendering it more effective in post-cracking energy absorption and deformation control compared to the longitudinal configuration. In comparison to CRS0, the CRSCLF model exhibited a 40% decrease in longitudinal elongation and a 45% reduction in residual due to the synergistic effect of steel fibers and longitudinal CFRP confinement.

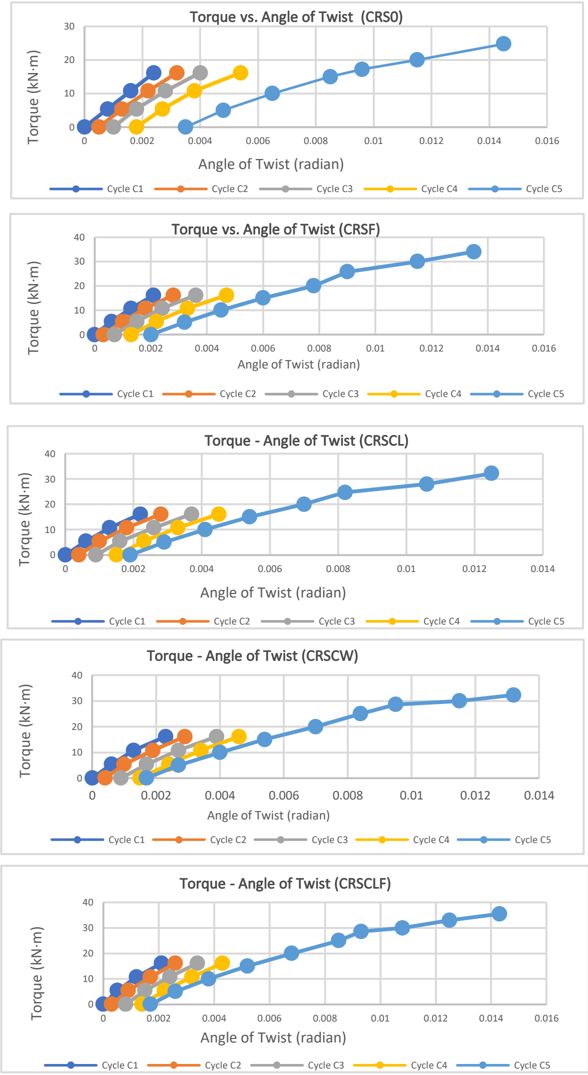

Figure 6. Torque-Angle of Twist

. 8. Stiffness

The ability of structural elements to resist deformations in response to applied loads is known as torsional stiffness (KT). It is a characteristic of rigidity (a material property). Structural members may have a rotational stiffness (KT), which is given by the equation KT = M/θ. Where: M = Applied moment (kN.m), θ = angle of twist (radian). This study calculated K_t at two key stages: (1) in the post-cracking range between the torque at the first visible crack (Kt-post) and the ultimate torque (Kt-u), indicating the reduction in stiffness after crack initiation; and (2) just at the ultimate torque stage, indicating the minimum stiffness before failure. The study evaluated the torsional stiffness of specimens using Kt-post and Kt-ult indicators. The CRSCL decreased elongation and residual by 25% and 30% relative to CRS0, but CRSCW achieved additional reductions of 45% and 50%, respectively. Both specimens exhibited linear behaviour before the first cracking. CRSCW showed a more gradual nonlinear transition after cracking. The transverse CFRP wrapping in CRSCW exhibited improved confinement and crack distribution, rendering it more effective in post-cracking energy absorption and deformation control compared to the longitudinal decrease in longitudinal elongation and a 45% reduction in residual relative to CRS0 due to the synergistic effect of steel fibers and longitudinal CFRP confinement

9. Conclusions

The experimental study of five reinforced concrete deep beams subjected to repeated pure torsion resulted in the following conclusions:

1.The use of longitudinal CFRP sheets improved the ultimate torque by approximately 30.8% compared to the control specimen. It also reduced the angle of twist and longitudinal elongation, indicating enhanced torsional stiffness and improved crack control. However, its confinement effect was limited compared to the wrapping method.

٢.The wrapped CFRP configuration achieved the highest increase in torsional capacity among all tested models, with a 46.2% improvement in ultimate torque. This method provided superior confinement, which significantly enhanced torsional resistance and post-cracking behavior compared to the longitudinal CFRP configuration.

٣.The beam reinforced only with steel fibers (CRSF) exhibited a 37.7% increase in ultimate torque over the control. It also showed clear reductions in deformation and residual elongation, confirming the efficiency of steel fibers in enhancing ductility and stiffness under repeated torsional loads.

٤.The combined strengthening technique (CRSCLF)، which involved both longitudinal CFRP sheets and steel fibers, resulted in a 43.7% improvement in ultimate torque. This hybrid system outperformed the longitudinal CFRP-only beam and demonstrated synergistic effects in enhancing both strength and deformation resistance.

٥.All strengthened beams exhibited improved torsional performance relative to the control beam. Among the applied techniques, CFRP wrapping proved to be the most effective in increasing torsional strength and post-cracking control under repeated pure torsional loading, followed by the combined CFRP–steel fibre configuration.

References

[1] ACI Committee, Building Code Requirements for Structural Concrete (ACI 318-19) and Commentary, ACI 318-19, American Concrete Institute, Farmington Hills, MI, 2019.

[2] ACI Committee 408, State-of-the-Art Report: Bond under Cyclic Loads, ACI 408.2R-92, pp. 1–5, 1999.

[3] Z. Dong, G. Wu, X.-L. Zhao, H. Zhu, and X. Shao, "Behaviors of hybrid beams composed of seawater sea-sand concrete and a prefabricated UHPC shell reinforced with FRP bars," Construction and Building Materials, vol. 213, pp. 32–42, 2019, DOI: 10.1016/j.conbuildmat.2019.04.059.

[4] J.G. Teng, J.F. Chen, S.T. Smith, and L. Lam, "Behaviour and strength of FRP-strengthened RC structures: a state-of-the-art review," Proceedings of the Institution of Civil Engineers - Structures and Buildings, vol. 156, no. 1, pp. 51–62, 2003, DOI: 10.1680/stbu.2003.156.1.51.

[5] M. Gaber, N.Z. Hassan, A. Abouzied, and H. Mamdouh, "Strengthening of reinforced concrete beams subjected to torsion and shear stresses using fibre-reinforced polymers (FRP)," Engineering Research Journal, vol. 128, pp. C82–C42, June 2024.

[6] B.S. Abduljalil, "Shear resistance of reinforced concrete deep beams with opening strengthened by CFRP strips," Journal of Engineering and Sustainable Development, vol. 18, no. 1, pp. 14–32, 2014.

[7] J.A. Khudair and R.S. Atea, "Shear behavior of self-compacting concrete deep beams strengthened with carbon fiber reinforced polymer sheets," International Journal of Engineering Research and Technology (IJERT), vol. 4, no. 2, pp. 187–191, 2015.

[8] M.A. Javed, M. Irfan, S. Khalid, Y. Chen, and S. Ahmed, "An experimental study on the shear strengthening of reinforced concrete deep beams with carbon fiber reinforced polymers," KSCE Journal of Civil Engineering, vol. 20, pp. 2802–2810, 2016.

[9] Central Organization for Standardization and Quality Control, Iraqi Specification No. 5: Portland Cement, Baghdad, Iraq, 1984.

[10] ASTM C150/C150M-17, Standard Specification for Portland Cement, ASTM International, West Conshohocken, PA, USA, 2017.

[11] ASTM A496-97ae1, Standard Specification for Steel Wire, Deformed, for Concrete Reinforcement, ASTM International, DOI: 10.1520/A0496-97AE01.

[12] British Standards Institution, BS 1881: Part 116:1983 — Method for Determination of Compressive Strength of Concrete Cubes, London, UK, 1983.

[13] ASTM C293-79, Standard Test Method for Flexural Strength of Concrete (Using Simple Beam with Center-Point Loading), ASTM International, Annual Book of ASTM Standards, Philadelphia, PA, 2014.

[14] ASTM C496-86, Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens, ASTM International, Annual Book of ASTM Standards, Philadelphia, PA, 2014.

[15] ASTM C469-02, Standard Test Method for Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression, ASTM International, Annual Book of ASTM Standards, Philadelphia, PA, 2014.