The International Journal of Energy & Engineering Sciences, 2022, 7 (1) 52-63
ISSN: 2602-294X - Gaziantep University

# EFFECT OF DIFFERENT TEMPERATURES ON THE SELF-COMPACTING CONCRETE CYLINDERS CONFINED WITH BFRP SHEETS, THE METHODOLOGY - PART A

Sara Kadhim* and Mustafa Özakça

Department of Civil Engineering, Gaziantep University, Gaziantep, Turkey
*Corresponding author, kadhimsara91@gmail.com

## ABSTRACT

Basalt fiber-reinforced polymers composite laminates have been widely used in recent years to improve and strengthen the flexural capacity of reinforced concrete (RC) elements. Basalt fibers outperform carbon laminates in terms of corrosion resistance, heat resistance, and ductility. However, there is a scarcity of knowledge about the mechanical properties of these laminates and their hybrid combinations when left in high heating regimes. The effect of higher heating regimes on the compressive strength of 21 unconfined and 21 confined concrete cylinders is investigated in this research. For 1, 2, and 3 hours, all of the cylinders were heated to 100 and 300 degrees Celsius. The compressive strengths of unwrapped concrete cylinders were compared to wrapped cylinders' counterparts. The extreme temperatures used in this investigation had essentially no effect on the compressive strength of the unwrapped cylinders; however, the wrapped specimens, particularly those covered with BFRP sheets, were severely affected.

**Key Words:** Compressive strength, basalt fiber reinforced polymers, temperature.

## 1. INTRODUCTION

Basalt Fiber reinforced polymers (BFRPs) have been widely accepted as a new material for strengthening and repairing civil engineering infrastructures around the world [1–3]. In many concrete constructions, such as bridges, parking garages, and concrete pavements, they have been employed as a replacement for conventional steel reinforcement [4–6]. BFRP jackets in columns are one of the most well-known applications of BFRPs. The exceptional properties of BFRP materials, such as superior strength, are attributed to the success of the BFRP strengthening procedure. Good corrosion resistance, lightweight and easiness of application. BFRPs are made of reinforcing fibers and cured resins (polymer matrix). The main load- carrying element in the BFRP is fibers. The polymer matrix guards the fibers from harms and permits loading distribution between singular fibers. Fiber choice is based on strength, stiffness and durability necessity for particular purpose. Resin selection is based on the kind of fibers, purpose and manufacturing. Fibers such as glass and carbon are being currently used in the construction industry and basalt fibers are being recently inserted. Several experiments on the compressive performance and related confinement processes of concrete cylinders coated in BFRP sheets have yielded several results. Records show that a properly built BFRP confinement can improve the concrete core's compressive strength, deformation ability, ductility, and energy absorption [7-35]. Insufficient research has been done on the behavior of externally bonded with Basalt FRP sheets building elements (columns, beams, slabs, etc.) when exposed to increased heating regimes. The goal of this investigation was to see how different heating regimes affected the behavior of concrete cylinders with basalt FRP jackets. An experimental examination involving the preparation and testing of 42 conventional 100 mm diameter x 200 mm height concrete cylinders was conducted to achieve the study's goal. Twenty-one cylinders were left unconfined, while the remaining twenty-one specimens were confined with one layer of BFRP jacket. Some of the specimens were left at ambient temperature, while others were heated to temperatures of 100°C and 300°C for 1, 2, and 3 hours, respectively. Cylinders were tested under uniaxial compression till failure after being exposed to high temperatures.

## 2. LITERATURE REVIEW

There are many related studies in the literature about the investigation of basalt fiber-reinforced polymers composite laminates.

Al-Salloum et al. [36] investigated the effects of a high-heat regime on 42 concrete cylinders encased in two different types of FRP sheets. Fourteen cylinders were left unwrapped, while the remaining 28 were encased in one layer of carbon and one layer of glass sheets, respectively. After that, the cylinders were left to cure for seven days at room temperature. The cylinders were kept in an oven for 1–3 hours before starting the compression test at temperatures of 100°C and 200°C. Then, a uniaxial compression test was performed on each cylinder until failure. The results demonstrated that at high temperatures and for long periods of time, unconfined cylinders showed significant strength loss, resulting in a rapid decline in concrete compressive strength. However, the remaining cylinders, which were encased in carbon and glass sheets, showed a lower loss of strength because the heat took a long time to travel to the concrete via the epoxy and the sheets. The results show that when exposed to a high heating regime, the compressive strength of the unconfined cylinder decreased significantly more than that of the confined ones. Furthermore, the test findings demonstrate that FRP laminates are easily impacted by fire.

Lenwari et al.[37] evaluated the axial compression behavior of conventional Ø150×300 mm concrete cylinders following exposure to increased temperatures of 300, 500, and 700°C for heating periods of 2 h (for all temperatures) and 3 h (only for 700°C) for heating periods of 2 h (for all temperatures). To explore the stress-strain correlations and failure modes of fire-damaged concrete before and after reinforcing with carbon fiber–reinforced polymer (CFRP) wraps, 192 specimens were tested in static compression. The test findings revealed that the postfire compressive strength, strain at compressive strength, and modulus of elasticity of concrete are influenced by the exposure temperature and time, unconfined concrete strength, and cooling method (air or water cooling). Low-strength concrete is more sensitive than high-strength concrete to the loss of residual characteristics induced by fire. After being exposed to high heating regimes, the CFRP wrapping can greatly improve the strength and ductility of concrete. CFRP confinement improves the strength of fire-damaged concrete more than it does for undamaged concrete. The confinement efficacy increases as the exposure temperature rises, notably for water-cooled concrete with the lowest strength (20 MPa). The level of ductility increase in fire-damaged concrete, on the other hand, is smaller than in undamaged concrete.

Bisby et al. [38] conducted the compressive tests on 33 standard concrete cylinders, of which 9 plain concrete cylinders were tested at ambient temperature, and the rest were heated to various elevated temperatures in an electric furnace (i.e., 300 ˚C, 500 ˚C and 700 ˚C), and then cooled to room temperature. The thermally damaged concrete cylinders were either unwrapped or wrapped with a single layer of carbon FRP (CFRP) jacket. The test results showed that after exposure to 300 ˚ C, 500 ˚ C or 700 ˚ C, the CFRP confinement of damaged concrete could increase the compressive strength of 32%, 53% or 66% on average, respectively. Moreover, the axial strains recorded at failure for the thermally damaged concrete wrapped with a single CFRP jacket layer were significantly enhanced compared with the unwrapped concrete.

## 3. TEST PROGRAM

### 3.1. Test Specimens

The current investigation used 42 concrete cylinders with a diameter of 100 mm and a height of 200 mm. The samples included 21 cylinders that were not contained and 21 cylinders that were confined with one layer of BFRP sheets. For 1, 2, and 3 hours, cylinders were subjected to temperatures of 100°C and 300°C. Following that, cylinders were subjected to uniaxial compression testing to failure, as per ASTM C39 test method [39]. Table 1 shows the test cylinders program, which included a duplicate of three specimens for each circumstance.

Table 1. Schedule of test specimens.

| Time of exposure (h) | Temperature (°C) | Unwrapped specimens | Wrapped with BFRP |
|---|---|---|---|
| ----- | Room | 3 | 3 |

| | | | |
|---|---|---|---|
| **1** | **100**<br>**300** | **3**<br>**3** | **3**<br>**3** |
| **2** | **100**<br>**300** | **3**<br>**3** | **3**<br>**3** |
| **3** | **100**<br>**300** | **3**<br>**3** | **3**<br>**3** |
| **Total number of specimens** | | **21** | **21** |
| | | **42** | |

### 3.2. Testing Materials

#### 3.2.1. Concrete

One moderate strength self-compacting concrete (SCC) mixture with the mix proportions shown in Table 2 was arranged to cast concrete. The process of concrete mixing was achieved with accordance to ASTM guidelines. Portland cement type 42.5R based on Turkish specifications TS EN 197 [40] was used in this work in addition to class F fly ash. The fly ash was supplied by Ceyhan Sugözü thermal power plant in Turkey. Table 2 lists the parameters of the cement and fly ash utilized. Natural local coarse aggregate with maximum size of aggregate of 10 mm was used with crushed river sand with a specific gravity of 2.6 and the grading shown in Fig. 1. Crushed sand with a maximum size of 2.36 mm, minimum size of 0.3 mm and specific gravity of 2.72 was used as fine aggregate. In addition, fine sand with a maximum size of 0.3 mm and specific gravity of 2.68 was used to enhance the workability of the mixture by increasing the fine materials. Viscocrete 30 superplasticizer was used to reach the required consistency of the mixture. With each patch of concrete, six 100 mm diameter and 200 mm depth cylinders were cast to acquire the compressive strength of the mixture. The beams and cylinders were water cured in standard conditions until the testing date at an age of 28 days. Fig. 3 shows pictures for the casting of the reinforced concrete beams. Three fresh tests according to EFNARC [41] requirements were conducted to evaluate the flowability and viscosity of the adopted SCC mixture, which were slump flow, T50 and V-funnel tests. The obtained diameter of slump flow test was 650 mm, while the recorded times for the T50 test and V-funnel test were 2.5 and 8.5 seconds, respectively. All recorded values fall within the limited values of EFNARC [41] indicating good SCC properties with acceptable filling ability and viscosity.

**Table 2**. Mix proportions in kg/m$^3$

| Cement | Fly ash | Coarse aggregate | Crushed Sand | Fine sand | Water | Super plasticizer | $f'_c$ (MPa) | Density |
|---|---|---|---|---|---|---|---|---|
| 275 | 285 | 710 | 651 | 217 | 188.1 | 2.77 | 49.8 | 2338.27 |

### 3.2.2. BFRP Sheets and Resin

The concrete cylinders were confining with unidirectional BFRP sheets. This type is known for its fire resistance, accessibility, smooth texture, durability, low price and high tensile strength as compared to others types of BFRP fabrics [42]. The used BFRP fabric has a thickness of 0.3 mm and a weight-to-area ratio of 0.3 kg/m2, while its tensile strength, modulus of elasticity and elongation are 2100 MPa, 105 GPa and 2.6%, respectively as shown Figure 1.

**Figure 1.** BFRP sheet sample.

An epoxy resin was used Master Brace SAT 4500 two-component epoxy adhesive was used to bond the BFRP fabric to the outer surface of the concrete as shown Figure 2. The compressive strength of this epoxy resin is greater than 60 MPa, the bending strength is greater than 50 MPa, and the bond strength is larger than 3 MPa. The epoxy-based adhesive was applied to the test samples in accordance with the manufacturer's user handbook.


**Figure 2.** Epoxy resin used for bonding of BFRP sheets.

### 3.3. Casting and Curing of Specimens

For concrete casting, sixty cylinders with an internal diameter of 100 mm and a height of 200 mm were used. To make it easier to remove the concrete cylinder after casting, oil was applied to the inside surfaces of the cylinder before casting. The cylinders were stored in the lab for one day after being cast in concrete. The concrete specimens were then taken out of the moulds and immersed in water for 28 days to cure. The sulphur capping process had conducted in order to be sure that the end surfaces of the specimen are perpendicular to the Paestum axis of test machine during the applying of the compression load. After 24 hours from conducting of the sulphur capping works, the cylinders will be ready to test compression with specimen's age f 28 days on the same day of testing. The final shape of specimens after sulphur capping is shown in Figure 3.

### 3.4. Application of BFRP Sheets

The BFRP sheets were applied in accordance with ISIS instructions and ACI440-2R requirements [43, 44]. The cylinders' surfaces were polished before confining the concrete with BFRP sheets. The two-component epoxy process, which included resin and hardener, was hand-mixed with care. Following that, the BFRP sheets were immediately applied to the cylinders' surfaces, providing lateral confinement in the hoop direction. The processes for covering the cylinder with BFRP sheets are shown in Figure 3. To provide sufficient time for epoxy curing, all cylinders were exposed to room temperature for at least 7 days. All cylinders were left at increased temperatures of 100°C and 300°C for 1, 2, and 3 hours before starting the test. The cylinders were then removed from the oven and allowed to cool in the lab temperature before being tested.

**Figure 3.** Steps of confining process and heating.

## 4. DISCUSSION

The results of wrapped and unwrapped test specimens will be summarized in Part B. The compressive strength values will be shown in the tables are the average of three samples.

### 4.1. Unwrapped Specimens

The heating systems were previously cleared and all of the unwrapped cylinders were left at room temperature. The cylinders were then put through a uniaxial compression test. Under axial load, the behavior of specimens was found to be consistent. The compressive strength of the unwrapped cylinders is shown in Table 3. Shearing and splitting of concrete were used to demonstrate the failure mode, as shown in Figure 6. It can be shown that the compressive strength of the unwrapped cylinders was unaffected by the elevated temperatures used in this study.

### 4.2. BFRP Wrapped Specimens

The compressive test results of the BFRP wrapped cylinders are shown in Table 4. When BFRP sheets were used to restrict the specimens, compared to unconfined specimens compressive strength increased somewhat (see Table 3). The temperature level had a substantial effect on the BFRP confined specimens, as shown in Table 4. When compared to wrapped specimens at ambient temperature, all specimens exposed to elevated temperatures demonstrated lower compressive strength. As demonstrated in Figure 5, increasing the temperature had a substantial impact on the compressive strength of the wrapped specimens. However, as compared to the effect of temperature level, the exposure period had a smaller impact on compressive strength. Figure 8 shows how the BFRP sheets changed color after being exposed to 300°C. This is a symptom of long-term deterioration in the BFRP sheets, which explains why the compressive strength of the BFRP wrapped specimens decreased after being subjected to high temperatures. This suggests that higher temperatures were more detrimental to BFRP sheets than to BFRP sheets.

### 4.3. Test Results Discuss

The average compressive strength of all test cylinders following exposure to various heating settings and exposure hours will be shown in Part B.

## 5. CONCLUSIONS

The goal of this study was to determine the compressive capacity of basalt FRP coated concrete cylinders after they were heated in an oven. The test contained 42 concrete cylinders, 21 of which were unconfined and 21 of which were confined with BFRP sheets. For 1, 2, and 3 hours, all of the cylinders were heated to 100°C and 300°C. Under similar conditions, the compression capacity of confined specimens with BFRP sheets was matched to that of unconfined specimens. The following results can be shown based on experimental records:

- The compressive strengths will be compared with unconfined cylinders. This raise is about 11%. This illustrated that BFRP sheets had a good influence on increasing the compressive strength of specimens PART B.
- All of confined concrete cylinders failed by splitting of the BFRP sheets.
- We will see that the increasing heat will have a significant influence on the compressive strength of the unwrapped cylinders. The compressive strength decreased as the heating degree or exposure hours increased..

## REFERENCES

[1] S.E.El-Gamal,*Behaviourofrestrainedconcretebridgedeckslabs reinforced with FRP reinforcing bars under concentrated loads [Ph.D. thesis]*, Universite de Sherbrooke, Que bec, Canada, 2005.

[2] S. E. El-Gamal, Y. Al-Salloum, S. Alsayed, and M. Aqel, "Performance of near surface mounted glass fiber reinforced polymer bars in concrete," *Journal of Reinforced Plastics and Composites*, vol. 31, no. 22, pp. 1501–1515, 2012.

[3] Y. A. Al-Salloum, S. E. El-Gamal, T. H. Almusallam, S. H. Alsayed, and M. Aqel, "Effect of harsh environmental condi- tions on the tensile properties of GFRP bars," *Composites Part B: Engineering*, vol. 45, no. 1, pp. 835–844, 2013.

[4] B.Benmokrane,E.El-Salakawy,A.El-Ragaby,andS.El-Gamal, "Performance evaluation of innovative concrete bridge deck slabs reinforced with fibre-reinforced-polymer bars," *Canadian Journal of Civil Engineering*, vol. 34, no. 3, pp. 298–310, 2007.

[5] M. Eisa, S. E. El-Gamal, E. El-Salakawy, and B. Benmokrane, "Design and construction of first GFRP-CRC200P slabs imple- mented on highway 40 east (Montreal)," in *Proceedings of the 37th Annual Conference of the Canadian Society for Civil Engineering*, pp. 1–8, Que bec City, Canada, 2008.

[6] S. E. El-Gamal, B. Benmokrane, E. El-Salakawy, P. Cousin, and A. Wiseman, "Durability and structural performance of carbon fibre reinforced polymer—reinforced

concrete parking garage slabs," *Canadian Journal of Civil Engineering*, vol. 36, no. 4, pp. 617–627, 2009.

[7]Y.L.Bai,J.G.Dai,M.Mohammadi,G.Lin,S.J.Mei,Stiffness-baseddesign-oriented compressive stress-strain model for large-rupture-strain (LRS) FRP-confined concrete, Compos. Struct. 223 (2019) 110953.

[8] J.G. Dai, Y.L. Bai, J.G. Teng, Behavior and modeling of concrete confined with FRP composites of large deformability, J. Compos. Construct. 15 (6) (2011) 963–973.

[9] T. Yu, J.G. Teng, Y.L. Wong, S.L. Dong, Finite element modeling of confined concrete-I: Drucker-Prager type plasticity model, Eng. Struct. 32 (3) (2010) 665–679.

[10] T. Yu, J.G. Teng, Y.L. Wong, S.L. Dong, Finite element modeling of confined concrete-II: plastic-damage model, Eng. Struct. 32 (3) (2010) 680–691.

[11] Y.L. Wang, G.P. Chen, B.L. Wan, G.C. Cai, Y.W. Zhang, Behavior of circular ice-filled self-luminous FRP tubular stub columns under axial compression, Construct. Build. Mater. 232 (30) (2020) 117287.

[12] Y.L. Wang, G.C. Cai, Y.Y. Li, D. Waldmann, A.S. Larbi, K.D. Tsavdaridis, Behavior of circular fiber-reinforced polymer-steel-confined concrete columns subjected to reversed cyclic loads: experimental studies and finite-element analysis, J. Struct. Eng. 145 (9) (2019), 04019085.

[13] J.G. Teng, J.L. Zhao, T. Yu, L.J. Li, Y.C. Guo, Behavior of FRP-confined compound concrete containing recycled concrete lumps, J. Compos. Construct. 20 (1) (2016), 0000602.

[14] Y. Zhou, X. Liu, F. Xing, H. Cui, L. Sui, Axial compressive behavior of FRP-confined lightweight aggregate concrete: an experimental study and stress-strain relation model, Construct. Build. Mater. 119 (2016) 1–15.

[15] J.J. Zeng, Y.Y. Ye, W.Y. Gao, S.T. Smith, Y.C. Guo, Stress-strain behavior of polyethylene terephthalate fiber-reinforced polymer-confined normal-, high-and ultra high-strength concrete, J. Build. Eng. 30 (2020) 101243.

[16] J.J. Zeng, W.Y. Gao, Z.J. Duan, Y.L. Bai, Y.C. Guo, L.J. Ouyang, Axial compressive behavior of polyethylene terephthalate/carbon FRP-confined seawater sea-sand concrete in circular columns, Construct. Build. Mater. 234 (2020) 117383.

[17] T. Ozbakkaloglu, J.C. Lim, T. Vincent, FRP-confined concrete in circular sections: review and assessment of stress-strain models, Eng. Struct. 49 (2013) 1068–1088.

[18] J.C. Lim, T. Ozbakkaloglu, Design model for FRP-confined normal- and high-strength concrete square and rectangular columns, Mag. Concr. Res. 66 (20) (2014) 1020–1035.

[19] D.Y. Wang, Z.Y. Wang, S.T. Smith, T. Yu, Seismic performance of CFRP-confined

circular high-strength concrete columns with high axial compression ratio, Construct. Build. Mater. 134 (2017) 91–103.

[20] Y.L. Bai, J.G. Dai, J.G. Teng, Monotonic stress-strain behaviour of steel rebars embedded in FRP-confined concrete including buckling, J. Compos. Construct. 21 (5) (2017), 04017043.

[21] L. Lam, J.G. Teng, Design-oriented stress-strain model for FRP-confined concrete, Construct. Build. Mater. 17 (6–7) (2003) 471–489.

[22] L. Lam, J.G. Teng, Ultimate condition of fiber reinforced polymer-confined concrete, J. Compos. Construct. 8 (6) (2004) 539–548.

[23] G. Lin, J.G. Teng, Three-dimensional finite-element analysis of FRP-confined circular concrete columns under eccentric loading, J. Compos. Construct. 21 (4) (2017), 04017003.

[24] G. Lin, J.G. Teng, Advanced stress-strain model for FRP-confined concrete in square columns, Compos. B Eng. 197 (2020) 108149.

[25] J.J. Zeng, Y.C. Guo, W.Y. Gao, L.J. Li, W.P. Chen, Stress-strain behavior of circular concrete columns partially wrapped with FRP strips, Compos. Struct. 200 (2018) 810–828.

[26] T. Ozbakkaloglu, J.C. Lim, Axial compressive behavior of FRP-confined concrete: experimental test database and a new design-oriented model, Compos. B Eng. 55 (2013) 607–634.

[27] T.M. Pham, M.N.S. Hadi, T.M. Tran, Maximum useable strain of FRP-confined concrete, Construct. Build. Mater. 83 (2015) 119–127.

[28] T.M. Pham, M.N.S. Hadi, Confinement model for FRP confined normal- and high-strength concrete circular columns, Construct. Build. Mater. 69 (2014) 83–90.

[29] J.J. Zeng, Y.C. Guo, W.Y. Gao, J.Z. Li, J.H. Xie, Behavior of partially and fully FRP-confined circularized square columns under axial compression, Construct. Build. Mater. 152 (2017) 319–332.

[30] A. Ilki, O. Peker, E. Karamuk, C. Demir, N. Kumbasar, FRP Retrofit of low and medium strength circular and rectangular reinforced concrete columns, J. Mater. Civ. Eng. 20 (2) (2008) 169–188.

[31] A. De Luca, F. Matta, A. Nanni, Behavior of full-scale glass fiber-reinforced polymer reinforced concrete columns under axial load, ACI Struct. J. 107 (5) (2010) 589–596.

[32] Y.C. Guo, W.Y. Gao, J.J. Zeng, Z.J. Duan, X.Y. Ni, K.D. Peng, Compressive behavior of FRP ring-confined concrete in circular columns: effects of specimen size and a new design-oriented stress-strain model, Construct. Build. Mater. 201 (2019) 350–368.

[33] A.A. Mohammed, A.C. Manalo, W. Ferdous, Y. Zhuge, P.V. Vijay, A.Q. Alkinani, A. Fam, State-of-the-art of prefabricated FRP composite jackets for structural repair, Eng. Sci. Technol. Int. J. 23 (5) (2020) 1244–1258.

[34] A. Siddika, M.A.A. Mamum, W. Ferdous, R. Alyousef, Performances, challenges and opportunities in strengthening reinforced concrete structures by using FRPs–A state-of-the-art review, Eng. Fail. Anal. 111 (2020) 104480.

[35] Y. Guo, J. Xie, Z. Xie, J. Zhong, Experimental study on compressive behavior of damaged normal- and high-strength concrete confined with CFRP laminates, Construct. Build. Mater. 107 (2016) 411–425.

[36] Y. Al-Salloum, H. Elsanadedy, A. Abadel, Behavior of FRP-confined concrete after high temperature exposure, Constr. Build. Mater. 25 (2) (2011) 838–850.

[37] Lenwari, A., Rungamornrat, J., & Woonprasert, S. (2016). Axial compression behavior of fire-damaged concrete cylinders confined with CFRP sheets. *Journal of Composites for Construction*, *20*(5), 04016027.

[38] L.A. Bisby, J.F. Chen, S.Q. Li, T.J. Stratford, N. Cueva, K. Crossling, Strengthening fire-damaged concrete by confinement with fibre-reinforced polymer wraps, Eng. Struct. 33 (12) (2011) 3381–3391.

[39] ASTM International, "Standard test method for compres- sive strength of cylindrical concrete specimens," ASTM C39, ASTM International, West Conshohocken, Pa, USA, 2015, http://www.astm.org/.

[40] TS EN 197-1:2012, Çimento-Bölüm 1: Genel çimentolar-Bileşim. özellikler ve uygunluk kriterleri (Cement Part 1: Composition. Specification and Conformity Criteria for Common Cements).

[41] EFNARC (2002) Specification and Guidelines for Self-Compacting. Concrete, Association House, Surrey, UK. www.efnarc.org

[42] Masoud, S., Soudki, K., Topper, T. "CFRP-strengthened and corroded RC beams under monotonic and fatigue loads", Journal of composites for construction, 5(4) pp. 228-236, 2001.

[43] ISIS Design Manual, *Strengthening Reinforced Concrete Structures with Externally Bonded Fibre Reinforced Polymers*, The Canadian Network of Centers of Excellence on Intelligent Sensing for Innovative Structures, ISIS Canada, University of Winnipeg, Manitoba, Canada, 2001.

[44] ACI 440.2R-08, *Guide for the Design and Construction of Exter- nally Bonded FRP Systems for Strengthening Concrete Strucutres*, American Concrete Institute, Farmington Hills, Mich, USA, 2008.