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Strengthening of concrete damaged by mechanical loading and elevated temperature

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Abstract. Despite being one of the most abundantly used construction materials because of its exceptional properties, concrete is susceptible to deterioration and damage due to various factors particularly corrosion, improper loading, poor workmanship and design discrepancies, and as a result concrete structures require retrofitting and strengthening. In recent times, Fiber Reinforced Polymer (FRP) composites have substituted the conventional techniques of retrofitting and strengthening of damaged concrete. Most of the research studies related to concrete strengthening using FRP have been performed on undamaged test specimens. This contribution presents the results of an experimental study in which concrete specimens were damaged by mechanical loading and elevated temperature in laboratory prior to application of Carbon Fiber Reinforced Polymer (CFRP) sheets for strengthening. The test specimens prepared using concrete of target compressive strength of 28 MPa at 28 days were subjected to compressive and splitting tensile testing up to failure and the intact pieces of the failed specimens were collected for the purpose of repair. In order to induce damage as a result of elevated temperature, the concrete cylinders were subjected to 400℃ and 800℃ temperature for two hours duration. Concrete cylinders damaged under compressive and split tensile loads were re-cast using concrete and rich cement-sand mortar, respectively and then strengthened using CFRP wrap. Concrete cylinders damaged due to elevated temperature were also strengthened using CFRP wrap. Re-cast and strengthened concrete cylinders were tested in compression and splitting tension. The obtained results revealed that re-casting of specimens damaged by mechanical loadings using concrete & mortar, and then strengthened by single layer CFRP wrap exhibited strength even higher than their original values. In case of specimens damaged by elevated temperature, the results indicated that concrete strength is significantly dropped and strengthening using CFRP wrap made it possible to not only recover the lost strength but also resulted in concrete strength greater than the original value.

Keywords: concrete; mechanical loading; elevated temperature; damage; strengthening; CFRP

1. Introduction

Concrete constitutes a major portion of the worldwide construction due to its remarkable durability. Ranging from large construction works involving dams, bridges, tunnels, monuments, highways and high-rise buildings to minor constructions like residential houses, foundations, walls and even small blocks, concrete has been used abundantly. The cheap availability of its constituent

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materials and less specialized skill requirements make concrete best suited for the construction industries of under developed and developing countries that do not possess the infrastructure involving newer and smart materials. However, there are certain factors that can influence the mechanical properties of concrete during its service life. Improper loading, incorrect design, poor workmanship, earthquakes, chemical exposures and low maintenance are among the various causes of damage in concrete like cracking, splitting, honey combing and other such defects.

The world's population is increasing at a rapid pace which is instigating the land, resource and economical limitations because of which it is not always possible to demolish and rebuild the damaged aging structures, particularly in developing countries. Researchers around the globe have employed several advanced materials like basalt fibers, ferrocement, stainless-steel wire-mesh and FRPs which are externally applied to concrete in order to enhance its loading capacity (Campione *et al.* 2015, Kaish *et al.* 2015, Napoli and Realfonzo 2016, Kumar and Patel 2016, Wu and Wang 2010, Attari *et al.* 2012, Kumutha *et al*. 2007). Concrete jacketing commonly employed for strengthening purposes has a major drawback of substantially increasing the cross-sectional area of the structural members which results in increased dead weight. Carbon fiber reinforced polymer (CFRP) and epoxy adhesives have gained popularity due to their high strength to weight ratios, corrosion resistance and capacity to handle large deformations (ACI 2008).

Severe exposure conditions like fire and elevated temperatures can have detrimental effects on concrete's micro-structure which in turn reduce the strength of the structure considerably. Concrete exhibits an exceptional resistance to fire and elevated temperatures up to a certain extent because its constituent materials possess low thermal conductivity when they are chemically combined but when the temperature approaches extremely high value; there are substantial changes in physical and chemical structure of concrete. Elevated temperature generally results in expansion of aggregates, water loss from Calcium Silicate Hydrate (C-S-H) and dissociation of calcium hydroxide in cement paste which eventually cause strength reduction or failure of structure (Omer 2007, Baher and Oguzhan 2010, Hager 2013). The effect of fire and elevated temperature on mechanical properties of concrete has been investigated extensively demonstrating the loss of strength at elevated temperatures particularly after 300℃ (Concrete Society 2008, Bisby *et al*. 2011, Freskakis 1979). A state-of-the-art review of research studies related to concrete properties at high temperature is available in (Qianmin *et al*. 2015).

To increase the loading capacity (strengthening) of RC structural members, use of CFRP and other fiber laminates has been studied extensively (Mehdi *et al.* 2018, Wensu *et al.* 2018, Attari *et al.* 2012, Jiangfeng *et al.* 2013, Rami *et al.* 2014, Meisami *et al.* 2015, Javed *et al*. 2016, Alaasda and Hassan 2017) and most of these studies have focused on strength enhancement of undamaged concrete specimens, and findings of such experimental studies may not be directly utilized for retrofitting of existing damaged or deteriorated structures. Limited research studies (Yaqub *et al.* 2013, Yaqub and Bailey 2011, Gao *et al.* 2018, Dan 2012, Kabir *et al.* 2018, Ruili *et al.* 2013, Gao *et al.* 2018) have been carried out in the past on retrofitting and strengthening of damaged concrete members using externally bonded FRP material and in most of such studies, damaged or loose portion of concrete was removed and gap was filled with epoxy mortar before externally applying FRP materials. The author's practical experience in the field of repair and strengthening of RC structures reveals that the cost of such epoxy mortars is comparable with the cost of FRP material in most of the cases and as a result, total cost of retrofitting method is certainly enhanced. Although few research studies have used cement mortar or concrete for the initial repair of damaged concrete before applying FRP (Gao *et al.* 2018, Dan 2012, Kabir *et al.* 2018), but still more research is required to high light the response of such retrofitted and/or strengthened concrete samples. This contribution presents the results of an experimental research study which was carried out in two phases: in first phase, behavior (strength and failure mode) of concrete cylinders which were fully damaged by mechanical loadings (compression and split tensile), repaired using cementitious materials and then strengthened by CFRP sheets, was investigated. Second phase deals with the mechanical behavior of concrete cylinders which were first damaged by elevated temperature of 400℃ and 800℃, and then strengthened by CFRP sheets.

2. Experimental program

The experimental work was divided in following two phases:

- **Phase-I** was designated for the retrofitting and strengthening of concrete cylinders damaged due to compressive and split tensile loadings. Eight cylinders were tested up to failure in compression while three cylinders were tested under split tensile loading up to failure. The cylinders damaged in compression were re-cast using fresh concrete of same characteristics and then strengthened using CRRP wrapping. The separated pieces of concrete cylinders loaded in split tensile loading were re-joined using rich cement mortar and then strengthened using single layer CFRP sheet.
- **Phase-II** was designated for the strengthening of concrete cylinders damaged due to elevated temperatures of 400℃ and 800℃. Twelve cylinders were exposed to each temperature value for two hours duration (Mohamedbhai 1986). Out of twelve cylinders, six were used for compression testing and remaining six were used for split tensile testing. Strengthening of the damaged concrete cylinders was done using single layer CFRP wrapping.

2.1 Concrete constituents

Ordinary Portland cement, locally available river sand as fine aggregates and crushed stone as coarse aggregates were used to make concrete of minimum target cylinder compressive strengths of 28 MPa. The concrete mix proportion was 1:1.5:3. The required number of concrete cylinders of standard size (150 mm diameter x 300 mm height) were cast and cured for 28 days. After curing, the specimens were subjected to mechanical loading and elevated temperature.

2.2 Damage by mechanical loading

Displacement controlled compressive strength tests were performed on cylinders at loading rate of 2 mm/minute. Just after the peak load, the tests were stopped and compressive strength of each tested sample was obtained. The relatively large intact pieces of each failed sample in compression as shown in Fig. 1, were collected for re-casting of cylinder and then strengthening with CFRP. Similarly, split tensile tests were also performed and peak load for each sample was recorded. At failure, cylinders were divided into two pieces as shown in Fig. 2 and for each sample; both half cylindrical pieces were collected and re-joined using rich cement-sand mortar, and then strengthened using CFRP sheet.

2.3 Damage by elevated temperature

Based on the review of the literature related to the effect of elevated temperature on the

Fig. 1 Intact pieces of specimens fully damaged in compression

Fig. 2 Cylinder subjected to split tensile loading

Fig. 3 Box furnaces

concrete properties presented in (Qianmin *et al*. 2015), two temperature values were selected for the purpose of this study: 400°C and 800°C. Further, the exposure period to these temperatures was kept 2 hours as major deterioration in concrete takes place during this time. The Box Furnaces as shown in Fig. 3 were used to heat the concrete specimens up to required temperature level. After exposure to elevated temperature, the physical state of each sample was observed. The concrete

Fig. 4 Surface condition of samples after exposure to elevated temperature

Fig. 5 Intact concrete placed in mold for re-concreting

cylinders exposed to 400^{o}C did not show any significant damage whereas the concrete cylinders subjected to 800^{o}C showed visible cracking and slight greenish color was also noticed on their surface as shown in Fig. 4.

2.4 Initial repair and retrofitting

The intact pieces of all eight concrete specimens failed in compression (refer to Fig. 1) were placed in steel molds as shown in Fig. 5 for re-concreting using mix having same constituents as that of old concrete. Before pouring concrete in each mold, fractured surface of old concrete was cleaned and moistened for better bond formation with new concrete. Compaction of each mold was done using vibrating table. Finally, the molds were covered by plastic sheets to avoid evaporation of water and de-molding was done after 24 hours of casting. Some of the samples after repair using fresh concrete are shown in Fig. 6. After 28 days of curing, the samples were left for drying. Four re-cast concrete cylinders were strengthened using full CFRP wrapping as shown in Fig. 7 and then testing under compressive loading. The remaining four cylinders were left unwrapped and re-tested in compression to investigate the regain in strength as of result of concrete repairing only.

Fig. 6 Re-cast concrete cylinders

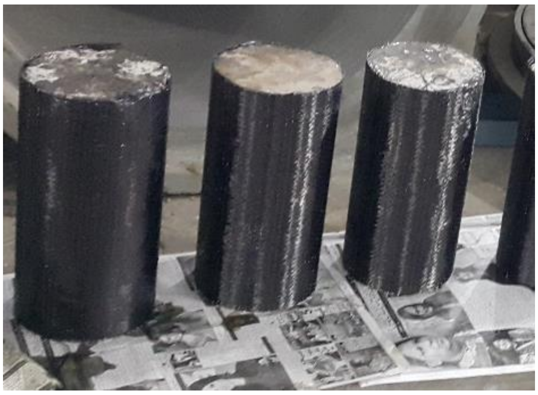

Fig. 7 Concrete cylinder strengthened using CFRP sheets

Fig. 8 Cement slurry applied on the inner surfaces of concrete cylinder

Fig. 9 Specimen after joining with mortar

Similarly, the samples failed under tensile loading were joined together as shown in Fig. 8 by first applying cement slurry on their surfaces and then using rich cement-sand (c/s) mortar having ratio of 1:1. Moreover, the gaps left at both sides of joined specimens were also filled with c/s mortar. The repaired samples were placed in molds used to cast cylindrical concrete samples and the molds were tightened for adequate bonding of the joined concrete pieces. The specimens were

Table 1 Properties of CFRP sheet

Material	CFRP
Fiber Type	High Strength Carbon Fibers
Laminate Design Thickness (mm)	0.12mm
Specific Weight.	0.022 g/cm^3
Modulus of Elasticity (fibers)	231 GPa
Ultimate Tensile Strength (fibers)	4100 MPa
Elongation at Break	1.7%

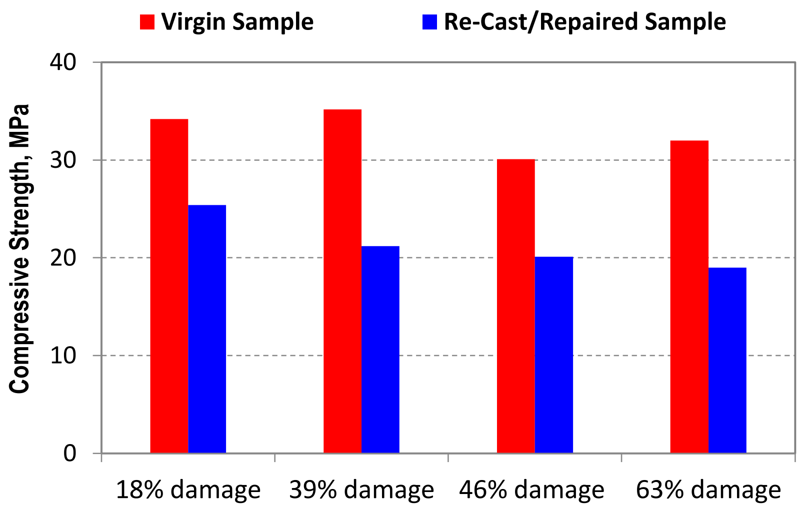

Fig. 10 Compressive strength of control and re-cast samples

removed from the molds after 24 hours and placed in curing room. Finally, the samples were strengthened using single layer CFRP sheet wrapping. Properties of CFRP are given in Table 1. Fig. 9 shows the final form of the repaired sample and also strengthened specimen.

As mentioned above, twelve concrete cylinders were subjected to elevated temperature of 400oC and same numbers of specimens were subjected to elevated temperature of 800℃. For compression testing, three concrete cylinders out twelve in each case were strengthened using single layer of CFRP-wrap and the remaining three were tested in compression in order to determine the loss of compressive strength due to elevated temperature. The strengthened specimens were also tested in compression to determine the recovery and increase in compressive strength. Similar methodology was adopted for split tensile testing.

3. Results and discussions

3.1 Compressive strength

Compressive strength values of re-cast samples containing old and new concrete and virgin concrete samples are shown in Fig. 10, where the level of damage in percentage (%) for each

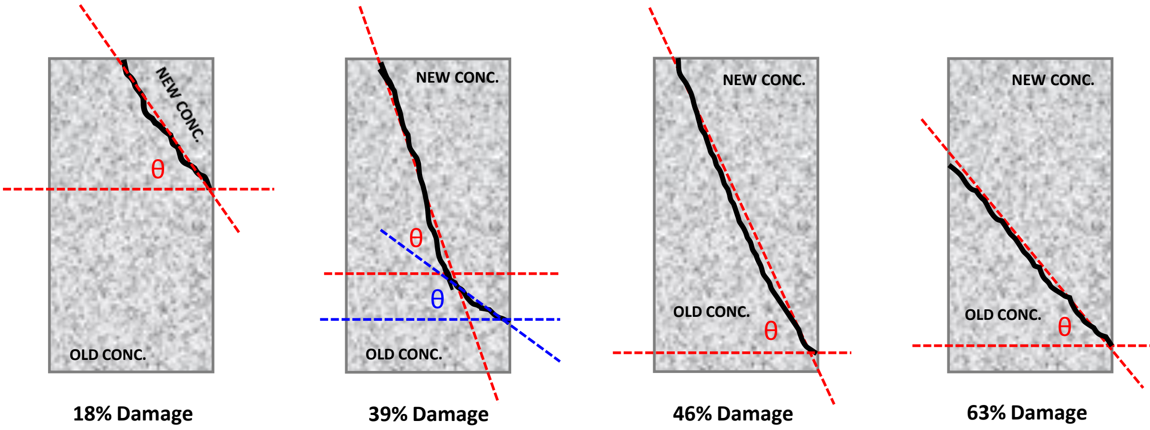

Fig. 11 Angle of failure surface with horizontal

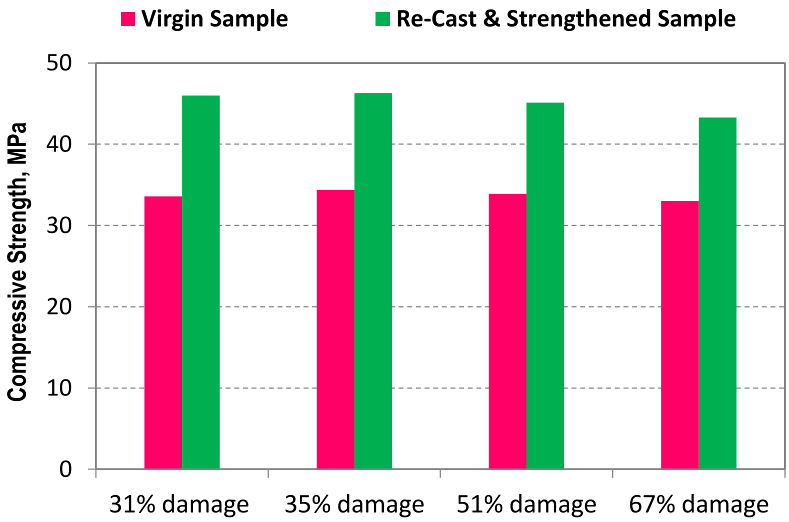

Fig. 12 Compressive strength of control and strengthened re-cast samples

sample was determined from the amount of new concrete that was required to re-cast a full cylinder. It is evident that the re-cast/repaired concrete samples were not able to achieve the original compressive strength (value obtained by virgin samples). Concrete cylinders with 18%, 39%, 46% and 63% damage level were able to achieve compressive strength which was 74%, 60%, 67% and 59% of their respective virgin concrete samples, respectively. It was observed that it was not only the initial damage level which could dictate the level of achievement of compressive strength of re-cast cylinders, but the shape of the intact piece obtained from damaged cylinders is also another important factor in the regard. It was noticed that angle of failure surface of damaged specimen with horizontal as shown in Fig. 11 is an important factor which directly influences the load carrying capacity of repaired/re-cast concrete cylinders. The results indicated that for relatively close damage levels more is the angle of failure surface, lesser is the compressive load carrying capacity of the re-cast/repaired specimen. Results presented in Fig. 12 show that the strengthening of repaired samples with single layer CFRP wrapping not only made it

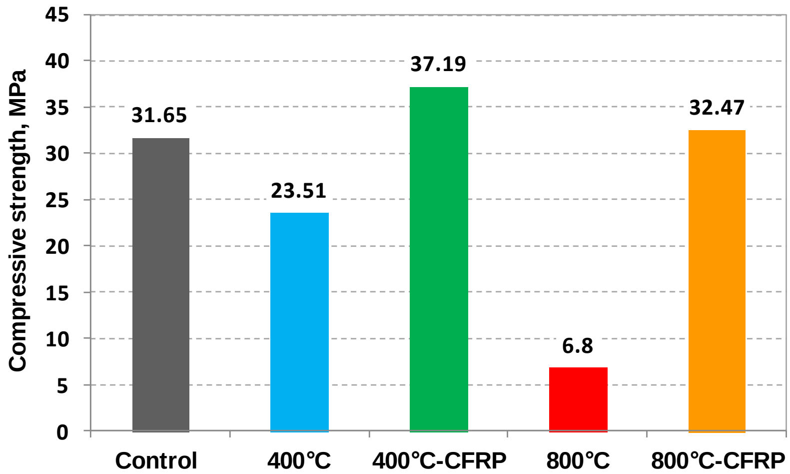

Fig. 13 Compression strength: effect of elevated temperature and strengthening

possible to regain the 100% original strength but also enhanced it. Concrete cylinders with 31%, 35%, 51% and 67% damage level were able to achieve compressive strength which was 37%, 35%, 33% and 31% more than the value obtained by their respective virgin concrete samples, respectively.

The results (average of three samples tested for each case) presented in Fig. 13 show that after exposure to elevated temperature, the compressive strength of the concrete was significantly dropped. Reduction in strength of 25.7% and 78.5% was observed when concrete was exposed to elevated temperature of 400℃ and 800℃, respectively. However, strengthening of such damaged concrete cylinders by wrapping of single layer of CFRP sheet resulted in not only full recovery of lost strength but also improved it in comparison of control concrete. For concrete cylinder damaged due to elevated temperature of 400℃ and 800℃, strengthening by CFRP wrap made it possible to get compressive strength 17.5% and 2.6% more than the control concrete, respectively.

3.2 Failure mode (compression)

Failure mode of re-cast specimens in compression is shown in Fig. 14, where it is evident that failure was occurred due to separation of old and new concrete (bond failure) under compressive load. In case of strengthened re-cast specimens, highly brittle failure occurred due to the sheet rupture as shown in Fig. 15; this indicates that the CFRP sheet was effectively utilized in enhancing the load carrying capacity of re-cast specimens. Under the application of load, de-bonding of new and old concrete surfaces resulted into more lateral deformation and consequently, more stress is transferred to CFRP sheet which led to significant enhancement in load carrying capacity of strengthened concrete cylinders. It was further observed that inside concrete was disintegrated into small pieces at final failure stage as evident in Fig. 15. Failure mode of heat damaged specimens in compression is shown in Fig. 16. More severe and distributed damage was observed in concrete cylinders subjected to 800℃ temperature which resulted in almost complete disintegration of cylindrical specimen. While in case of concrete cylinders subjected to 400℃ temperature, failure in compression was almost similar to that observed in case of control samples; local crushing of concrete at ends or a distinct crack passing throughout the height of cylinder.

Fig. 14 Failure mode in compression (re-cast samples)

Fig. 15 Failure mode in compression (re-cast & strengthened specimens)

3.3 Split tensile strength

Split tensile strength values are presented in Fig. 17, where it is clear that two halves of a concrete cylinder separated in split tensile test but rejoined with cement-sand mortar and then strengthened using CFRP wrapping, were able to develop tensile strength even greater than the original value. Split tensile strength of sample 1, 2 & 3 was observed to be 53%m 47% & 42% more than the respective original value, respectively.

Results of split tensile test performed on healthy concrete cylinders, concrete cylinders damaged as a result of exposure to elevated temperatures of 400^{o}C and 800^{o}C and strengthening concrete cylinders are presented in Fig. 18. Three cylinders were tested for each case and average values are presented here. It is clear from these results that tensile strength of concrete is significantly reduced due to elevated temperature. A drop of 21% and 84% in tensile strength was noticed when subjected to elevated temperature of 400^{o}C and 800^{o}C, respectively. Strengthening of concrete cylinders damaged due to exposure temperature of 400^{o}C using CFRP wrapping

Fig. 16 Failure mode in compression (heated samples)

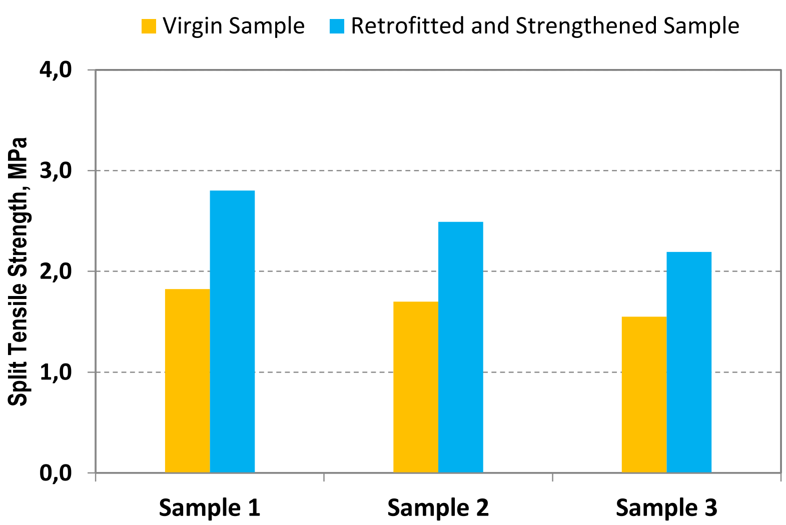

Fig. 17 Split tensile strength

resulted in split tensile strength which was 84% higher than the strength value of control concrete. However, strengthening of concrete cylinders damaged due to exposure temperature of 800^{o}C using the same strengthening technique resulted in split tensile strength almost similar to the value exhibited by the control concrete. These results indicate that it is possible to regain the tensile strength of the concrete which is lost due to exposure to elevated temperature for two hours by employing single layered CFRP wrap.

3.4 Failure mode (splitting tension)

Typical failure mode of strengthened concrete cylinder tested for split tensile strength is shown in Fig. 19 where it is clear that failure occurred due to local crushing of concrete and CFRP sheet under loading line rather than tensile rupture or de-bonding of CFRP sheet. Healthy concrete and un-strengthened heat damaged concrete samples were failed by splitting into two halves.

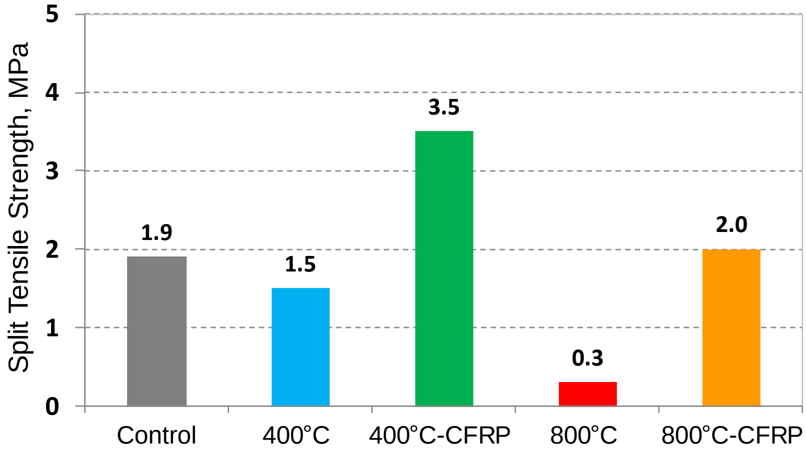

Fig. 18 Split tensile strength: effect of elevated temperature and strengthening

Fig. 19 Failure mode in splitting tensile test

4. Conclusions

Findings of the research study presented in this contribution have made it possible to draw the following conclusions:

1. For fully damaged concrete cylinder in compression, it was possible to restore its 60% to 70% of the original compressive strength by re-casting the cylinder using old intact concrete and fresh concrete of same mechanical characteristics. Presence of a distinct weaker plane between old and new concrete is the reason behind the less strength restoration by this technique.
2. Re-casting of cylinders using old intact concrete and new concrete, and then strengthening using CFRP wrapping could make it possible not only to restore 100% compressive strength but also resulted in strength more than the original. Nature of the failure of the concrete cylinders at ultimate compressive load after strengthening with CFRP wrapping was generally very brittle as a result of CRFP rupture.
3. Joining of two halves of concrete cylinders separated during split tensile loading using rich

cement-sand mortar and then strengthening by single layer CFRP wrapping made it possible to get tensile strength even greater than the original value. Failure of such specimen under split tensile loading was governed by local crushing of CFRP sheet along the loading line.

4. Exposure to elevated temperature of 400°C and 800°C caused reduction of 25.7% and 78.5% in compressive strength of concrete, respectively. Strengthening of damaged cylinders using single layer CFRP wrapping not only made it possible to recover 100% lost strength but also enhanced it as compared to the original value. Average improvement in compressive strength compared to control concrete was 17.5% and 2.5% for strengthened samples which were damaged due to elevated temperature of 400°C and 800°C, respectively. Brittle failure due to CFRP sheet rupture instead of de-bonding was the final mode of failure in all strengthened specimens.

5. Split tensile strength of concrete was dropped by 21% and 84% when exposed to elevated temperature of 400°C and 800°C for two hours, respectively. However, strengthening of such heat damaged concrete cylinders using full CFRP wrapping not only made it possible to recover 100% lost strength but also enhanced it by 84% compared to control concrete value for samples exposed to temperature of 400°C.

Hence, repair of damaged concrete element using cement mortar or concrete instead of using epoxy mortar or epoxy adhesives before strengthening with CFRP sheets is a feasible approach and this may reduce the final cost of retrofitting/strengthening project in the field.

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