

Effect of Elevated Temperature on Flexural Behavior of RC Beams with NSM CFRP

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Abstract

The strengthening of RC structures with fiber reinforced polymer (FRP) materials has demonstrated enormous potential as a repairing material. However, their thermal and mechanical behaviors after exposure to elevated temperature remain an obstacle due to FRP's sensitivity to high temperatures as compared with other structural materials. In this paper an experimental work was conducted to study the behavior of RC beam with NSM CFRP with different adhesive materials exposed to elevated temperature of 550°C for different periods of time and cooling schemes. In this experimental study 6 beams were cast, one beam (BN) was not exposed to elevated temperature as a control beam and the remaining beams were exposed to elevated temperature. These beams were tested under four-point loading. The effect of variables was studied in terms of ultimate failure load, maximum deflection and failure mode. From the test results, it could be concluded that ready-mix mortar could be an alternative adhesive material. The ultimate load-carrying capacity of the RC beam was reduced for longer duration of elevated temperature.

Keywords: RC beams; NSM; CFRP; Elevated temperature; Adhesive materials

Introduction

During the past years, various systems for repairing reinforced concrete structures using fiber reinforced polymers (FRPs) have been developed. These systems can be used, essentially by bonding FRP plates, sheets, or strips to the exterior surfaces of reinforced concrete members with a structural adhesive such as an epoxy polymer resin, to strengthen concrete beams and slabs in both flexure and shear, to increase the strength of structural connections [1]. There is a little readily available information on FRP performance at elevated temperature, as would be experienced in hot service environments (70°C to 200°C) or during well-developed building fires (exceed 1000°C), or after exposure to elevated temperatures resulting from various causes [2].

The most common strengthening technique is based on the application of the FRP on the surface of the elements to be strengthened and is designated as externally bonded reinforcement (EBR) technique. Recent research has revealed that this technique cannot mobilize the full tensile strength of FRP materials due to premature de-bonding; several attempts have been made to overcome the defects of EBR. Strengthening with near-surface mounted (NSM) CFRP which is based on the concept of bonding glass or carbon FRP rods or laminates into pre-cut grooves opened in the concrete cover of the elements to be strengthened [3].

Strengthening of reinforced concrete beams using near surface mounted (NSM) CFRP strips provided higher strength capacity than externally bonded (EB) CFRP strips using the same material with the same axial stiffness. The NSM CFRP reinforcing bars or strips limited the deflections and crack widths [4,5].

The beams strengthened with EB CFRP; their capacity increased by 25% and the ductility reduced due to the brittle failure caused by the occurrence of end debonding of the CFRP reinforcement. However, the reinforcement with NSM bars has enhanced the performances of the strengthened beams both in terms of failure load and ductility if compared with the beams strengthened with an equivalent amount of EBR; moreover the failure mode in the NSM bars strengthened beams was the crushing of concrete in compression [6].

The main mode of failure for most of the tested specimens with epoxy adhesive was concrete-tension failure accompanied with or without epoxy cracking (splitting or debonding). Specimens with longer bonded length failed by CFRP bar rapture. The main mode of failure for the specimens with cement adhesive was adhesive splitting at the concrete-cement interface. These specimens showed a failure load of about 40 to 56% of that of their counterparts with epoxy adhesive [7,8]. The response of CFRP RC beams depends mainly on the concrete cover and the temperature profiles inside the beams, the CFRP temperatures decrease with increasing the concrete cover, and CFRP reinforced concrete beams exhibited significant degradation in shear and flexural strengths [9].

In visual observation of concrete samples subjected to elevated temperatures, it was noticed that the surface cracks became visible when the temperature reached 600°C. The cracks were very pronounced at 800°C and increased extremely when the temperature increased to 1000°C. According to color image analysis, intensity of the yellow color increased with increase in temperature and red color appeared when the temperature increased to 800°C. Therefore, it seemed that the results of color image analysis may also be used to assess the level of temperature to which the concrete was subjected [10].

The NSM CFRP strengthening system bonded using epoxy may be capable of withstanding over 40 min at 100°C, but less than 10 min at 200°C. The performance at high temperature of NSM CFRP strengthening systems can be improved considerably by using a cementitious grout adhesive. The cementitious adhesive system was able to support the sustained load for more than 4 hrs at 100°C

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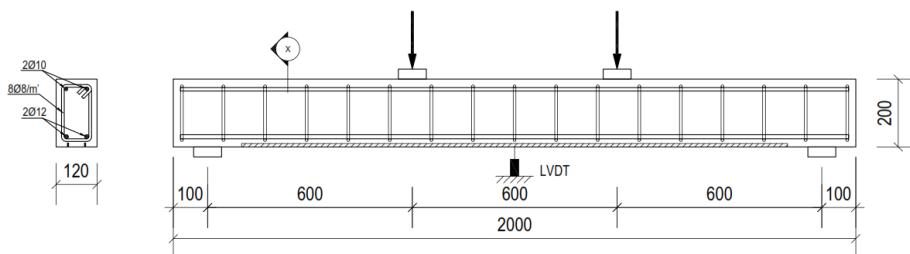


Figure 1: Detail of beam reinforcement with experimental setup.

Beam Specimen	Adhesive Material	Heating Time (hrs)	Cooling Scheme
BN	Epoxy	-	-
BE-2-A	Epoxy	2	Air
BC-2-A	Cement Mortar	2	Air
BR-2-A	Ready-mix Mortar	2	Air
BE-2-W	Epoxy	2	Water
BE-4-A	Epoxy	4	Air

Table 1: Detail of beam specimens.



Figure 2: Experimental setup.

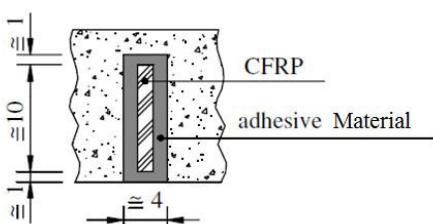


Figure 3: Detail of CFRP orientation in groove.

and for more than 70 min at 200°C. The externally bonded FRP strengthening system bonded with epoxy was capable of withstanding more than 4 hrs at 100°C and more than 80 min at 200°C [11,12].

Experimental investigations

The tested RC beam specimens were designed according to Egyptian specification code. The nominal value of compressive strength of concrete (f_c) is 40 MPa. The longitudinal steel reinforcement was steel bars with nominal yield strength (f_y) of 360 MPa. The stirrups were mild steel with nominal yield strength of 240 MPa. The manufacturer specified the tensile strength and modulus of elasticity of the CFRP sheets were 3100 MPa and 165 GPa, respectively. In

the experimental program, a total of 6 RC beam specimens were tested to failure under four point loading to investigate the flexural behavior including ultimate load, ultimate deflection and failure model; after exposure to elevated temperature for different periods of time and cooling schemes.

Materials and Methods

Ordinary Portland cement (CEM I 42.5N) was used. The water cement ratio was 0.5. The coarse aggregate was 25 mm dolomite. Fine sand as fine aggregate was used. The main reinforcement bars was 2Ø12 at bottom, and 2Ø10 at top. The web reinforcement was closed stirrups of 8 mm with spacing of 125 mm. The thickness of the concrete cover is 25 mm on the lateral and upper faces of the beam and 40 mm on the bottom one. CFRP was rectangular profile with 1.4 × 10 mm cross section of 1600 mm overall length. Three types of adhesive materials were used; epoxy, cement mortar and ready mixed mortar based on cement modified with emulsified synthetic polymers.

Specimens

All the tested beams were rectangular in cross-section having the dimensions width (b) of 120 mm, height (H) of 200 mm with effective depth (d) of 180 mm. The overall length (L) is 2000 mm with span length (l) of 1800 mm. Figure 1 and Table 1 give details of the tested beams. Figure 2 shows the test setup for flexural test. In order to make it easy to recognize the description of each beam, abbreviation of words had been used. So alphabetic letter "N" will refer to the beam with no exposure to elevated temperature; and "E, C and R" will refer to the type of adhesive material that is epoxy, cement mortar and ready-mix mortar, respectively. "2 and 4" will refer to heating time, respectively. "A and W" will refer to cooling schemes that is in air and by water, respectively.

CFRP installation

After 28 days of curing; two grooves of about 4 mm width and 12 mm depth were cut in the concrete cover on the tension face of the beam, using a diamond cutter, and then cleaned by compressed air. Adhesive materials were prepared according to the supplier recommendations which applied in groove then faces of CFRP strips. One layer of CFRP was inserted to the paste in the groove; the surface is leveled and the excess adhesive material is removed. Figure 3 show CFRP orientation in groove. At least five days were spent on the curing/hardening process of the adhesive material, before testing the beam.

Elevated temperature test procedure

The tested beams were subjected to an elevated temperature equal to 550°C from all sides for 2 or 4 hours. Figure 4 shows the setup of exposure to elevated temperature. The electrical furnace with height equals 600 mm while their side length equals 250 mm and all beams

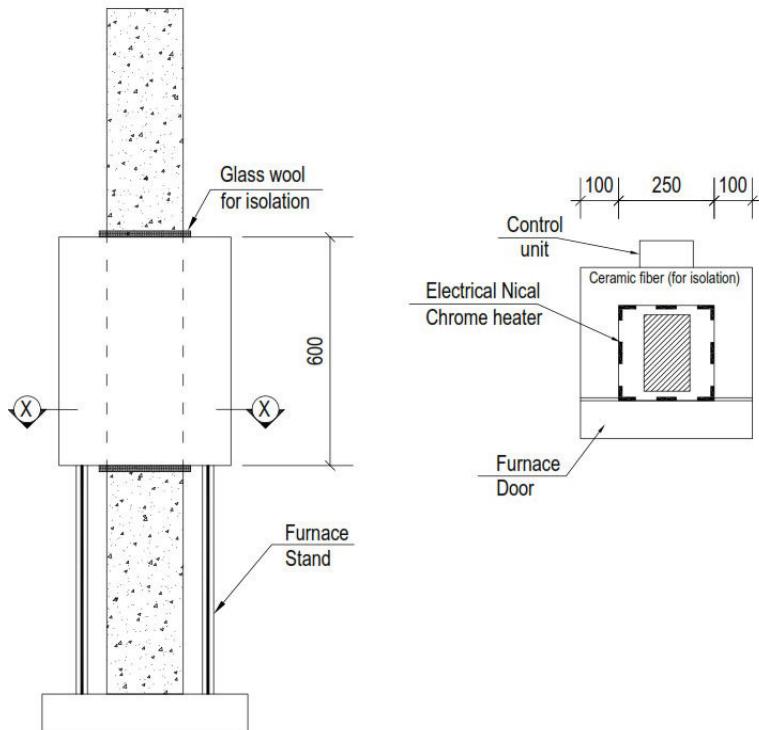


Figure 4: Setup of the exposure to elevated temperature from all sides.

Beam Specimen	P _u (kN)	Δmax (mm)	Initial Crack Load (kN)	Mode of Failure
BN	79.2	34.67	15	Crushing of concrete at compression zone
BE-2-A	69.0	40.47	11	Crushing of concrete at compression zone and tension zone with rupture of FRP resin
BC-2-A	60.0	43.14	9	Crushing of concrete at compression zone
BR-2-A	66.7	48.46	9	Crushing of concrete at compression zone with rupture of FRP resin
BE-2-W	61.5	38.57	8.5	Crushing of concrete at compression zone with rupture of FRP resin
BE-4-A	56.7	42.26	7	Crushing of concrete at compression zone and tension zone with rupture of FRP resin

Table 2: Test results.

were inserted along the regular square cross section, centered with the beam's length. The furnace was made of outside steel plate casing lined with ceramic fiber for isolation and provided with electrical Nical Chrome heaters. The furnace opening was surrounded by glass wool to prevent or reduce the losses of the elevated temperatures.

After the exposure to the elevated temperatures, the heated beams were cooled gradually in air for 24 hours before testing except BE-2-W which was cooled by gradually spraying water for 3 hours before testing. In addition, visual inspection was done to determine the color change in the exposed concrete surfaces of the heated beams. After that, the flexural behavior was examined.

Items of investigation

At the age of 35 days, RC beam specimens were tested to investigate the effect of elevated temperature on the behavior of concrete beams strengthened with NSM FRP. This experimental study focuses on:

1. The effect of different adhesive materials (epoxy, cement mortar and ready-mix mortar).
2. The effect of different heating time (2 hrs and 4 hrs).
3. The effect of different cooling schemes (air and water).

Experimental Results and Discussion

The test results are summarized in Table 2. The table shows ultimate failure load (P_u) and maximum deflection (Δ_{max}) for all the beam specimens. The deflections were measured at the mid span by using + 200 mm linear variable differential transducers (LVDTs). It was observed that all beams showed typical crushing of concrete at compression zone as shown in Figure 5. And Figure 6 shows the applied load versus mid-span deflection behavior of all beam specimens.

Effect of different adhesive materials

To study the effect of different adhesive materials, epoxy, cement mortar and ready- mix mortar were investigated. Figures 7 and 8 show the comparison of beam specimens in this section. The test results showed a reduction in strength by 13% due to exposure beam to elevated temperature of 550°C for 2 hrs when epoxy used as adhesive material. When cement mortar used, the strength reduced by 24%, whereas when ready-mix mortar used, the reduction in strength was by 16%. The specimens produced deflection of 17%, 24% and 40% more than (BN) when used epoxy, cement mortar and ready-mix mortar, respectively.

The beam strengthened using epoxy (BE-2-A) achieved much

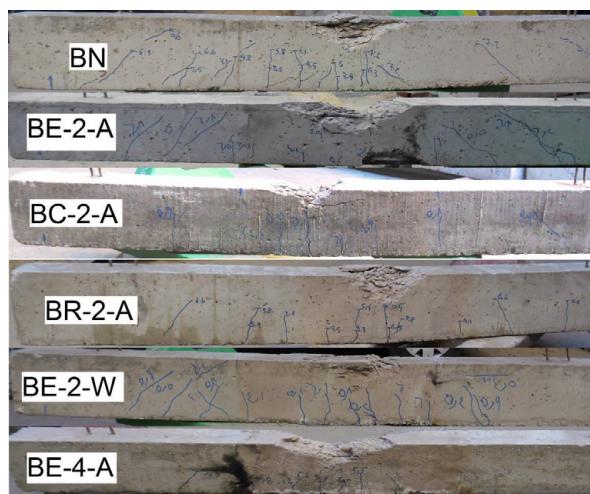


Figure 5: Mode of failure of specimens.

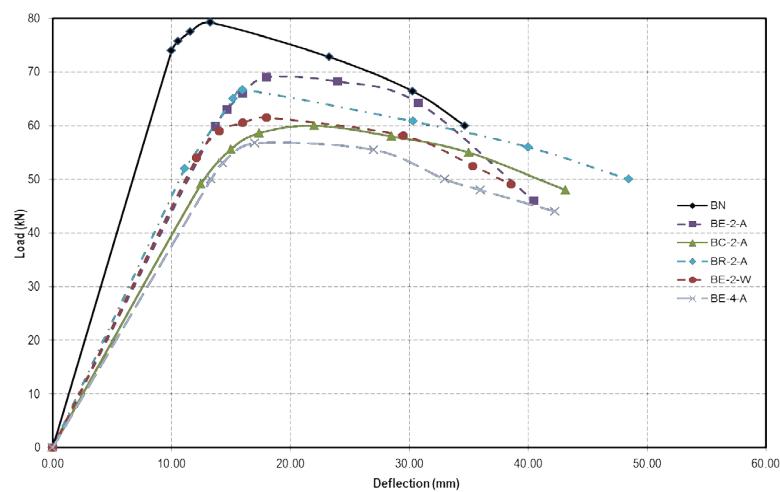


Figure 6: Load – deflection curve for all beam specimens.

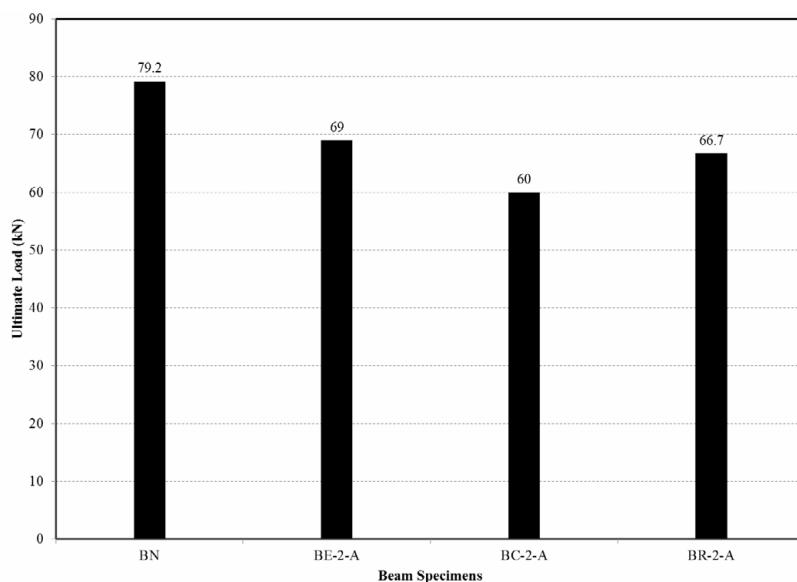


Figure 7: Effect of adhesive materials on ultimate failure load.

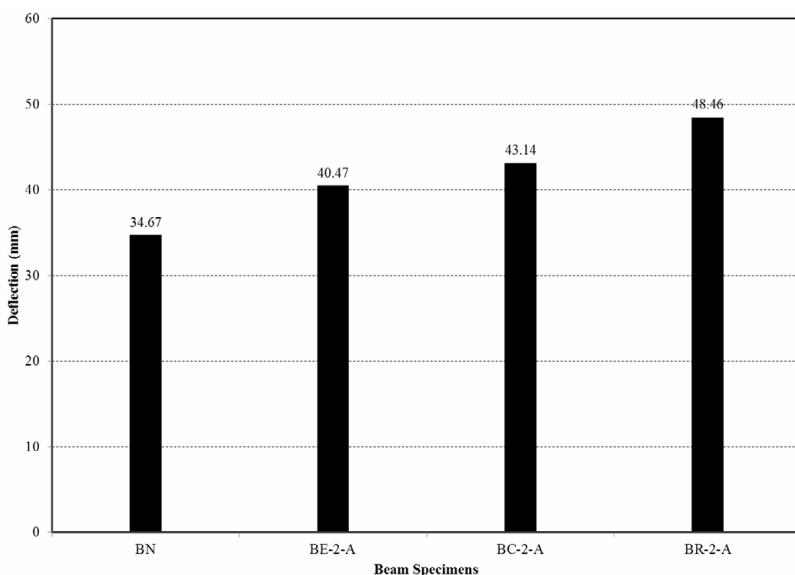


Figure 8: Effect of adhesive materials on max deflection.

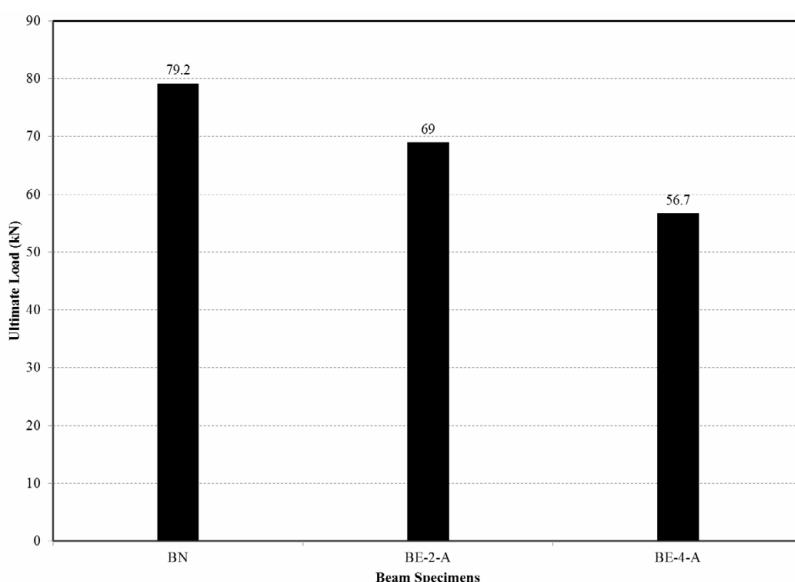


Figure 9: Effect of time periods on ultimate failure load.

higher strengths compared to those strengthened with cement mortar, or ready-mix mortar, it failed by FRP rupture with crushing of concrete. Beam (BR-2-A) failed same way and achieved close strength with slightly more stiff responses than the epoxy adhesive strengthened beam.

Effect of different heating time

To study the effect of heating time of 2 and 4 hours was investigated. Figures 9 and 10 show the comparison of beam specimens in this section. The test results showed that exposure to elevated temperature of 550°C for 2 hrs caused average reduction in ultimate load about (13%), while for 4 hrs caused average reduction about (29%). However, the max deflection was more than control beam (BN) about 17% and 22% for 2 and 4 hours respectively. At higher exposure time, there is more degradation in the strength of heated concrete.

Effect of different cooling schemes

To study the effect of cooling schemes of air and water was investigated. Figures 11 and 12 show the comparison of beam specimens in this section. The test results showed that using air to cool specimens caused average reduction in ultimate load about (13%), while using water caused average reduction about (22%) in ultimate load and increase about (11%) in max deflection. The water cooling caused the largest reduction in the stiffness of concrete. This is due to the fact that there is a steep thermal gradient in the concrete during the cooling which causes more damage than the natural cooling.

Conclusions

Based on the results of this experimental investigation, it could be concluded that:

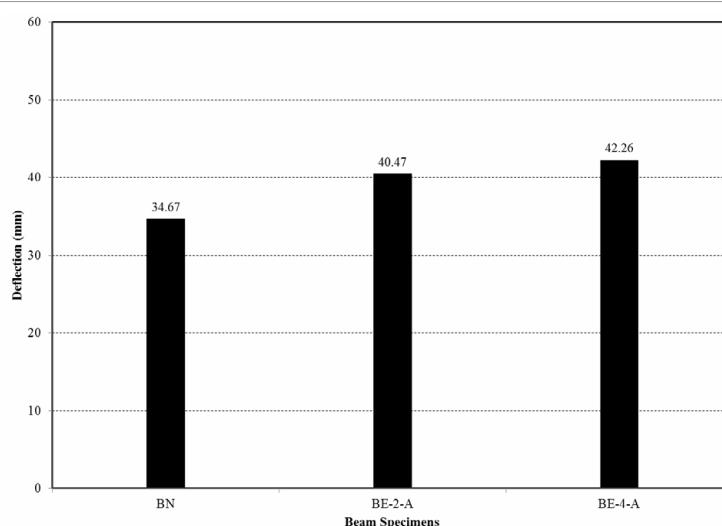


Figure 10: Effect of time periods on max deflection.

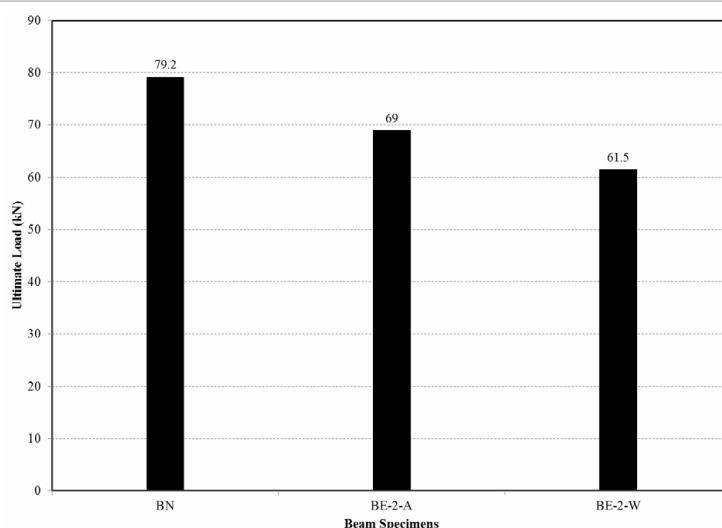


Figure 11: Effect of cooling scheme on ultimate failure load.

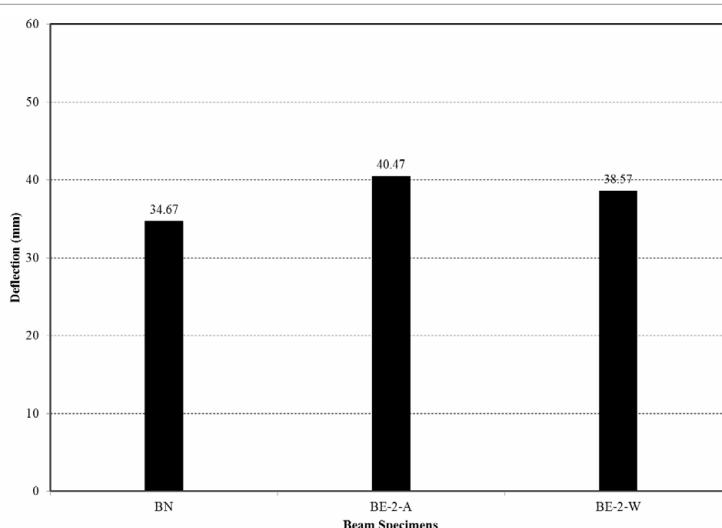


Figure 12: Effect of cooling scheme on max deflection.

1. Adhesive material showed a significant effect on the capacity of beams. Using cement mortar decreases the capacity by 13%, whereas using ready-mix mortar decreases the capacity by 3.3%. The mentioned values were compared to that with epoxy as an adhesive material.

2. The ready-mix mortar could be alternative adhesive material to epoxy.

3. Applying elevated temperature for longer period of time significantly reduced the capacity by 18%.

4. Cooling scheme significantly affected the capacity of beams. When the beam cooled by water, the capacity decreased by 22%.

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