Mechanical and Dynamic Recovery Behavior of Fire Damage Concrete Under Different Post Fire Curing Techniques

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Abstract. Post-fire curing has proven to be an effective repair method in restoring the structural integrity of concrete structures affected by fire. Various post-fire curing methods have been explored in previous research; however, the practical feasibility of these methods remains a major concern. An experimental investigation is carried out to evaluate the effects of two distinct post-fire curing techniques on the strength recovery of fire-damaged concrete cylinders. The employed methods include a) submerged water tank curing and b) water curing using jute bags, both administered over a 28-day period. The study assesses the influence of these post-fire curing techniques on the restoration of mechanical and dynamic properties through Uniaxial Compressive Strength, Ultrasonic Pulse Velocity (UPV), and Impact Hammer Modal Testing. Experimental results reveal that both curing methods exhibit notable effects on residual compressive strength and dynamic recovery of concrete cylinders following exposure to elevated temperatures. Significantly, the application of jute bags for curing also produces positive results, indicating its practical suitability as a repair method for concrete structures exposed to fire incidents.

Keywords: Post-fire curing methods, submerged water tank curing, water curing using jute bags, dynamic properties, mechanical properties.

1 Introduction

Concrete is a prominent material known for its exceptional compressive strength and resistance to environmental factors such as freeze-thaw cycles. However, exposure to elevated temperatures can lead to chemical and physical changes, resulting in the deterioration of its mechanical and dynamic characteristics. The heightened vapor pressure induced by elevated temperatures in concrete, coupled with its limited thermal conductivity, establishes a thermal gradient from the outer surface to the core, causing thermal expansion and significant stresses. These stresses initiate cracks, leading to a decline in the material's overall strength [1-4]. These studies indicate a proportional decrease in compressive strength with rising temperatures, particularly beyond 300°C. Evaporation

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of free physically bound water within aggregate and the cement matrix initiates at 110°C, causing increased capillary porosity and microcracks. Dehydration and ettringite depletion within the cement matrix occur in the 80-150°C range. At 120–350°C, the dehydration of calcium silicate hydrate and the decomposition of gypsum accelerate, contributing to strength degradation [5-7]. Negative effects on compressive strength are less pronounced below 300°C, and in some situations, minor increase is observed due to water evaporation accelerating cement hydration. The breakdown of calcium hydroxide and silicate hydrate causes a notable 50% decrease in compressive strength over 500°C. Temperatures exceeding 800°C led to decarbonation of carbonate and increased decomposition of C–S–H, causing a 70% reduction in compressive strength. Above 1000°C, almost all compressive strength is lost [1, 4, 8, 9].

The conventional method for restoring fire-damaged concrete involves costly procedures like replacing compromised layers with fresh concrete. Recent studies suggest potential property recovery through post-fire curing techniques, such as ponding, wet curing, and sprinkling [10-12]. However, these methods require extended curing periods. There is a need for further research to devise more efficient and practical post-fire curing techniques.

As per the authors' knowledge, no prior studies have specifically investigated the effects of curing methods utilizing jute bags on the mechanical and dynamic characteristics of concrete that has been subjected to fire damage. This paper explores the effect of post-fire water curing using jute bags on the mechanical and dynamic properties of concrete exposed to high temperatures. By comparing two post-fire curing methods – recuring using jute bag and submerged water tank curing – this study quantitatively assesses compressive and dynamic strength recovery. A number of tests were conducted on samples prior to fire exposure, following fire damage, and after applying post-fire curing methods to analyze strength recovery.

2 Methodology

2.1 Material

Local ordinary Portland cement (Bestway Cement) was utilized as the cementitious material is listed in Table 1. Fine aggregate consisting of river sand with a fineness modulus of 2.81, readily accessible in the area, was utilized. Coarse aggregates of 9.5mm and 19mm were used. To optimize workability and reduce water consumption, an admixture like BASF 802 was added, details of the mix proportions are shown in Table 2. Total Twenty-five cylinders were cast and subsequently placed in a curing tank for a 28-day period as shown in Fig.1a. Cylinder labels and descriptions are provided in Table 3.

2.2 High temperature exposure and curing methods

In a muffle furnace, cylinders were exposed to high temperatures between 100°C and 700°C. Before placing in the muffle furnace the samples were placed in a cage-like

Table 1. Chemical Composition of OPC (Bestway Cement) [13]

Oxides	*SiO2*	*Al2O3*	*Fe2O3*	*CaO*	*MgO*	*K2O*	*SO3*	*LOI3*	*IR4*	*SrO*	*TiO2*	*Free Lime*
	21	5.04	3.24	61.7	2.56	-	1.51	1.83	0.54	-	-	0.98

Table 2. Mix Design

Cement content OPC (Bestway) kg	*Fine Aggregate sand (Lawrancepur) kg*	*Coarse Aggregate 19mm 40% (Margalla) kg*	*Coarse Aggregate 9.5mm 60% (Margalla) kg*	*Water (Potable) liter*	*Admixture (BASF 802) Liter*
390	390	481	722	183	3.90

Table 3. Cylinder labels and descriptions

Sample ID	*Description*	*Curing method*	*Curing Duration*
BF	Before fire damage	-	-
FDx	After fire damage	-	-
WCRx	Water tank curing repair	Submerged water tank curing	28
JBRx	Jute bag curing repair	Jute bag curing	28

"x" for all samples represents the temperature to which each sample was exposed

structure for protection against spalling. Cylinders were placed in the furnace as shown in Fig.2a and subjected to a controlled heating rate of 6°C/min. Each cylinder in the furnace, upon reaching the desired temperature, was maintained for 2 hours to achieve consistent external temperature distribution from the surface to the core. The cylinders were cooled in the furnace (with power supply off) before testing to avoid uneven cooling and thermal stresses. Fig.3 depicts fire damaged cylinders, for better visibility cracks are marked with red lines. Only those cylinders that were subjected to temperatures as high as 500°C, 600°C, and 700°C showed signs of cracking. Therefore, the crack profiles of only these cylinders are drawn.

(a) (b) (c)

Fig. 1. Curing methods, a) submerged water tank curing, b), c) water curing with jute bag

(a) **(b)**

Fig. 2. Heating of cylinders, a) cylinder with cage in furnace, b) muffle furnace

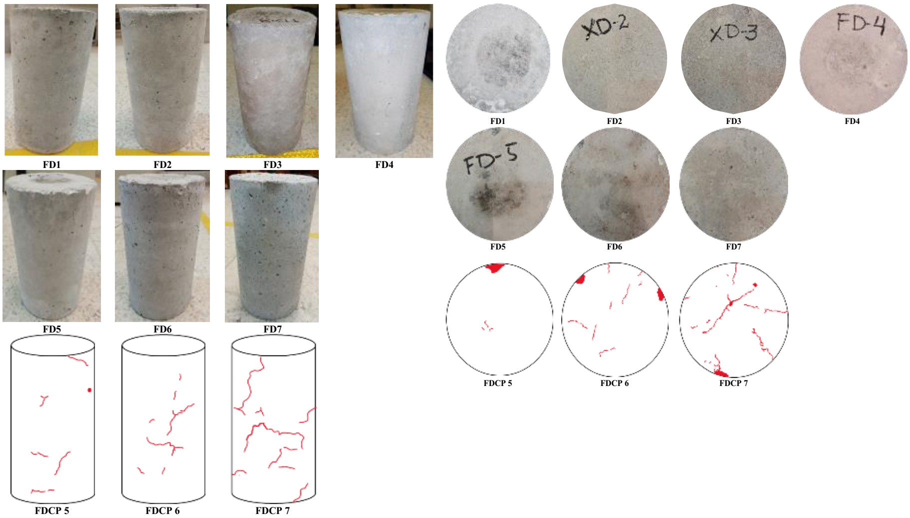

Fig. 3. Post fire-damage of cylinders front face and top surface with red crack markings

Two post-fire curing methods were employed as repair methods to recover strength in concrete specimens. Submerged Water Tank Curing, also known as ponding, is an effective method for post-fire strength recovery, ensuring maximum residual compressive strength [14]. Cylinders were placed in a curing tank at room temperature (20-25°C) for 28 days, employing potable water with a pH of 6 for the recuring process as shown in Fig. 1. Considering previous research on concrete curing utilizing jute bags, this study introduces a novel post-fire curing technique using jute bags. Cylinders exposed to fire were wrapped in jute bags, ensuring optimal contact, and watered thrice daily for 28 days.

2.3 Measurements

To evaluate the dynamic and mechanical recovery of various destructive and non-destructive tests were conducted before and after exposure to heat, as well as post-fire curing. The uniaxial compressive strength was determined using a Universal Testing Machine (UTM) that has a loading rate of 0.5 KN/s and a maximum capacity of 1500 KN. Ultrasonic pulse velocities (UPV) were assessed with a pulse meter and transducer pair (40 kHz to 50 kHz), using a direct transmission mode at the International Islamic University Islamabad. Weight loss and density measurements were conducted by weighing specimens before and after heat exposure. Dynamic properties like frequency and damping were determined using modal testing. This method involves exciting the structure with a known force and measuring the response with an accelerometer. Data processing in DADiSP software was done to calculate damping and frequency from acceleration data. Recently [3, 15] used this software to calculate dynamic properties of concrete using acceleration data collected from either hammer strike or drop ball methods.

3 RESULTS AND DISCUSSIONS

3.1 Weight loss and density

Seven series of samples has been taken including 3 samples for each series to study the impact of high temperatures on the characteristics of concrete. Fig.4a shows the average weight loss of seven specimens. The average weight loss of cylinders exposed to 400°C and 500°C are 5.2%, 5.6% and 6.3%, respectively. However, at 600°C and 700°C the weight loss specimens increase to 6.3% and 6.8% respectively. The observed trend in Fig.4 suggests that the impact of fire on the concrete specimen becomes more severe with increasing temperatures ranging from 100 to 700 °C. It is interesting to note that as within temperature 500°C, the percentage loss in weight starts to escalate more rapidly. This phenomenon is caused by the breakdown of calcium hydroxide and the deterioration of the cement matrix, leading to increased porosity and strength loss. Beyond 500°C, the degradation of the aggregates and cementitious materials occurs, which results in crack formation produced more noticeable cracks and weight loss as observed in Fig.3 and Fig.4a. It is clear that exposing concrete to temperatures exceeding 400°C results in a higher weight loss, because the removal of water from the concrete increases with the rising temperature. range (100°C-300°C), the average weight loss percentage is low i.e. 1.5% to 4.8% as compared to high temperatures. It is because at this temperature range dehydration reactions occur in which the chemically bond water in the cement paste begins to evaporate. It results in a steady reduction of weight, but the structural integrity may still be maintained.

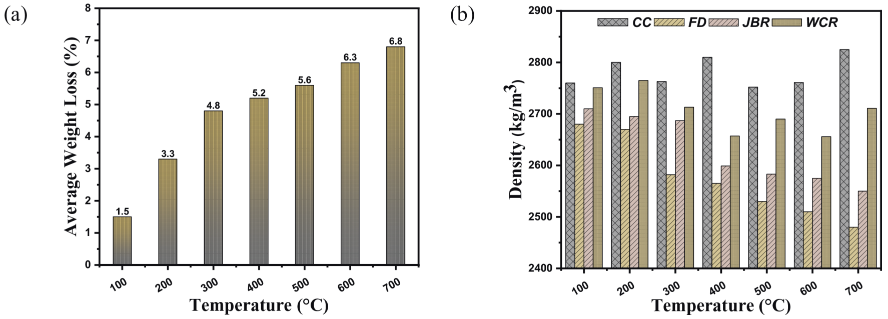

Fig. 4. (a) Average weight loss percentage of cylinders after exposed to elevated temperatures (b) Density comparison of cylinders before, after high temperature exposure and after post fire curing

From the Fig.4b, it is observed that till 200°C temperature we haven't notice any significant difference in the density. This is because of the removal of free water from the sample. However, as we go beyond 300°C we observe a significant loss of material density. It is observed that at 700°C the density of control specimen is 2825kg/m^3 but after exposure to high temperature it reaches up to 2438kg/m^3 that means 14% loss of the material density. This attributed to evaporation of bonded water, contraction of cement pastes and the expansion of volume of siliceous aggregate particles which cause cracking and eventually resulted in the decrease of density. Fig.4b shows the density comparison of cylinders before, after high temperature exposure and after post fire curing. Both methods improved the density after burning, but WCR consistently restored density closer to its original values, with smaller variations at each temperature level. For instance, at 400°C, WCR increased density to 2657 kg/m^3 compared to JBR's 2599 kg/m^3. This suggests that water curing offers superior performance in restoring concrete density after fire damage, likely due to its ability to maintain higher moisture levels, promoting better hydration and recovery.

3.2 Effects of post fire water curing on Compressive Strength

The compressive strength of a concrete cylinder is determined by the maximum axial stress it can withstand before failure occurs. The undamaged non repaired concrete specimens were taken as the control concrete (CC) samples. The compressive strength of these control samples is compared with that of the fire damaged samples repaired by water tank curing and curing using jute bags techniques. Figure.5 illustrates the decline and subsequent recovery of compressive strength in fire-damaged concrete cylinders subjected to temperatures between 100 and 700 °C, both before and after repair. It is observed that from 100 to 300 °C the rate of reduction is less however after 400 °C the compressive strength reduced drastically (i.e. 28.79 to 3.13 MPa). When exposed to temperatures less than 300°C, the compressive strength shows a small decline, largely due to the dehydration of bound water. However, significant chemical changes in the concrete occurred between 300°C and 500°C, leading to a decrease in compressive strength and an increase in porosity. This is evident from Fig. 5, which shows that samples at 400°C, 500°C, 600°C, and 700°C for two hours lost 55.78%, 77%, 80.03%, and 89.51% of their final compressive strengths. At temperature 400°C, the concrete lost almost half of his compressive strength as compared of the undamaged specimen. Notably, the compressive strength of FD cylinder decreased by up to 90% when subjected to a maximum temperature of 700 °C. The significant reduction in compressive strength can be linked to the thermal deterioration of cement paste and aggregates.

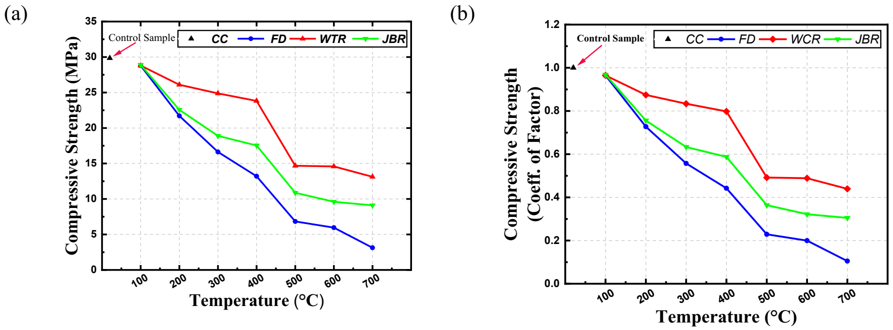

Fig. 5. (a) Comparison of compressive strengths for two recuring techniques and exposed temperature. (b) Comparison of Coefficient of Factor for two different recuring methods across different temperatures.

Two repairing methods are employed to reinstate the lost compressive strength after fire damage-one involving jute bags and the other using water tank curing for 28 days as is evident from Fig.1. The JBR technique effectively restored the compressive strength of fire-damaged concrete cylinders to 26%, 18%, 15%, and 22% at various temperatures from 400 to 700°C, compared to fire-damaged cylinders. This is because of the fact that jute bag helps to retain moisture and regulate the temperature, which is important for the proper curing of the concrete. This process helps to prevent cracking and ensures that the concrete reaches its full strength. Jute bag allows for the exchange of air and moisture, while still providing protection from excessive drying or rapid temperature changes. The second repairing technique is water tank curing repair (WCR). WCR involves the continuous immersion of the concrete cylinders in water tank, which facilitates the continuation of hydration reactions in the cement paste. Interestingly, for the FD cylinders, almost 64%, 34%, 36%, 37% of the compressive strength is recovered by the water tank curing of cylinders for 28 days for the exposure temperature of 400°C to 700°C for 1hr respectively. This improvement is possible due to the moist environment which causes rehydration of the cement. However, this technique gives some level of protection and support to the damaged concrete, but to restore the compressive strength JBR impact is relatively limited compared to WCR method. This shows that with the increase in temperature, the regain of the compressive strength through repair techniques decreases in general. [9-11].

Fig.5 represents the residual compressive strength of cylinders after fire damage with the effects of different repair methods. It is noteworthy that at 700°C, the residual capacity is less than 10% of its original value and a drastic change is observed after 300°C. For the jute bags repair technique, it increased the capacity to 20% as the coefficient of factor jumps from 0.1 to 0.3 at 700°C as evident from Fig.5. However, the repair is unable to create more impact relative to water tank curing technique. As the WCR able to regain the compressive strength about 37% at 700°C.

3.3 Ultrasonic pulse velocities (UPV)

In order to determine the effect of high temperatures on ultrasonic pulse velocities, concrete cylinders were exposed to temperature ranges between 100°C and 700°C.The results revealed a consistent trend. With rising temperatures, the ultrasonic pulse velocities of the concrete cylinders steadily decreased. At lower temperatures (100°C to 300°C), initial reductions in ultrasonic pulse velocities were observed. This could be attributed to the effects of thermal expansion and the initiation of dehydration processes within the concrete. Beyond 500°C, the concrete's microstructure underwent severe alterations, resulting in a substantial decrease in ultrasonic pulse velocities. The results of UPV clearly indicated the reduction in concrete quality from outstanding (3908 m/s) to good (2390 m/s), unsure (1767 m/s), not well (872 m/s) and low (325 m/s) when in contact to high temperatures 400°C, 500°C, 600°C and 700° C, respectively (see Fig.6).

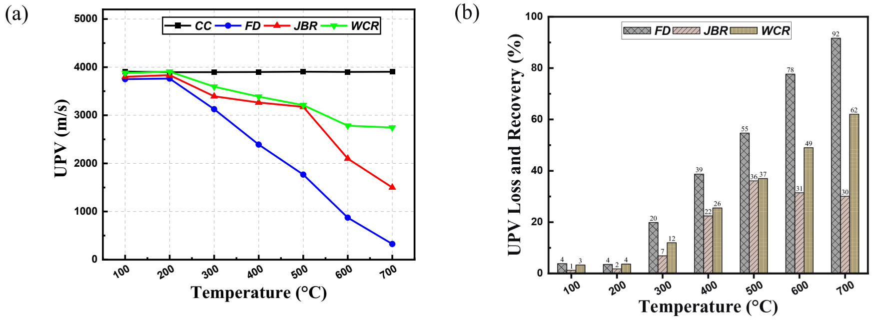

Fig. 6. (a) Comparison of Ultrasonic pulse velocities of damaged cylinders with the repaired cylinders at different temperature. (b) Percentage damage and repair by Jute Bag and water tank curing technique for ultrasonic pulse velocity

The results of UPV in Fig.6 showed that for the water curing repair technique for 28 days, the concrete quality has improved sufficiently from excellent (3387 m/s), good (3210 m/s), medium (2783 m/s) and fair (2745 m/s) at their respected temperatures. Similarly, for the JBR the concrete has regained strength quite sufficiently as the UPV values are (3265 m/s), (3175 m/s), (2100 m/s), and (1500 m/s) at the exposed temperature range 400 to 700°C which is quite significant improvement.

A comparison is made between the percentage reduction in UPV due to fire damage and the percentage recovery achieved through jute bag and water curing techniques, as shown in Fig. 6b. As seen from the figure that after 400°C a significant improvement is seen in the UPV value by using JBR i.e. 22% repair at 400°C up to 30% repair at 700°C. In contrast, the impact of water curing method is high as the UPV value improved 26% at 400°C and the maximum (62%) repair is observed at 700°C.

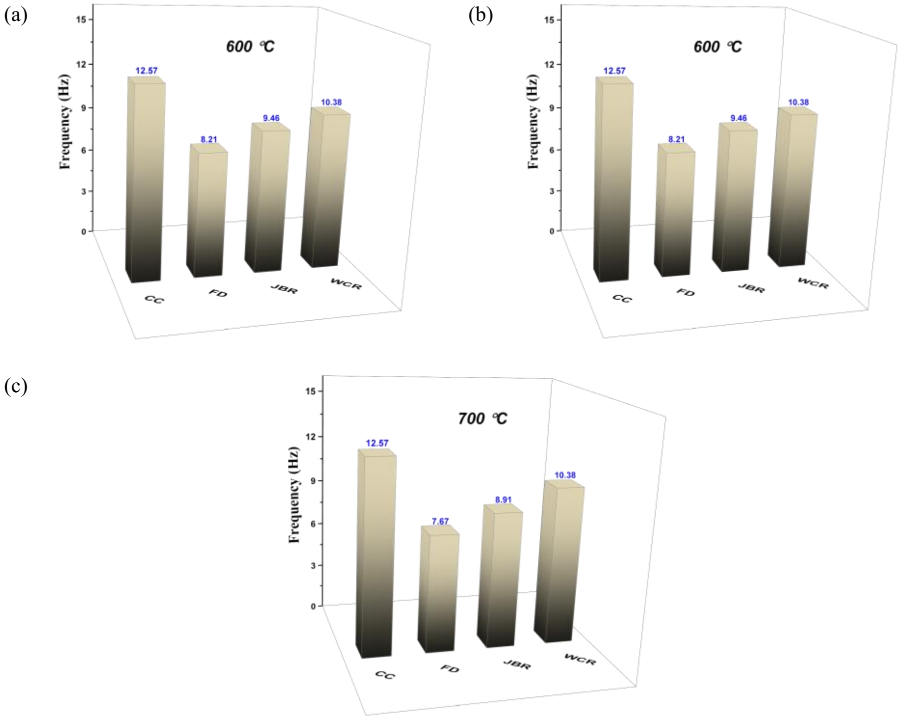

Fig. 7. Comparison of natural frequencies of cylinders for different post fire curing techniques and exposed temperature, a) at 500°C, b) at 600°C, c) at 700°C

3.4 Frequency

The dynamic properties of concrete, including natural frequencies and damping, undergo changes when exposed to elevated temperatures. Recent research, as indicated by [11], has reported a decline in the natural frequencies of concrete beams during exposure to fire, followed by improvement after water curing. This frequency change is primarily attributed to variations in the post-fire and re-curing stiffness of concrete. In Fig.7, the reduction in natural frequency for a FD cylinder at 500°C (8.96 Hz) is depicted, compared to the controlled specimen (12.57 Hz), attributed to same factors as explained in compressive strength section. The impact of fire damage becomes more pronounced at temperatures exceeding 500°C. Hence, modal testing is specifically conducted on samples exposed to temperatures beyond 500°C to analyze and understand the consequential changes in dynamic properties. Post-fire repair techniques, including Jute Bag Repair (JBR) and Water Tank Curing Repair (WCR) for 28 days, were applied. It is observed that the frequency is regained (9.51Hz) for JBR and (10.68Hz) for WCR, is potentially attributed to the hydration of un-hydrated cement facilitated by presence of water. Water curing using Jute bags also significantly improved the dynamic characteristics of concrete, however water tank curing proved to be a more successful curing repair method. A similar trend was observed at 600°C, and at 700°C, where more damage occurred, the frequency dropped drastically to 7.67 Hz from the controlled sample (12.57 Hz). However, the repairing techniques improved the natural frequency to 8.91 Hz through the JBR and 10.38 Hz through WCR methods.

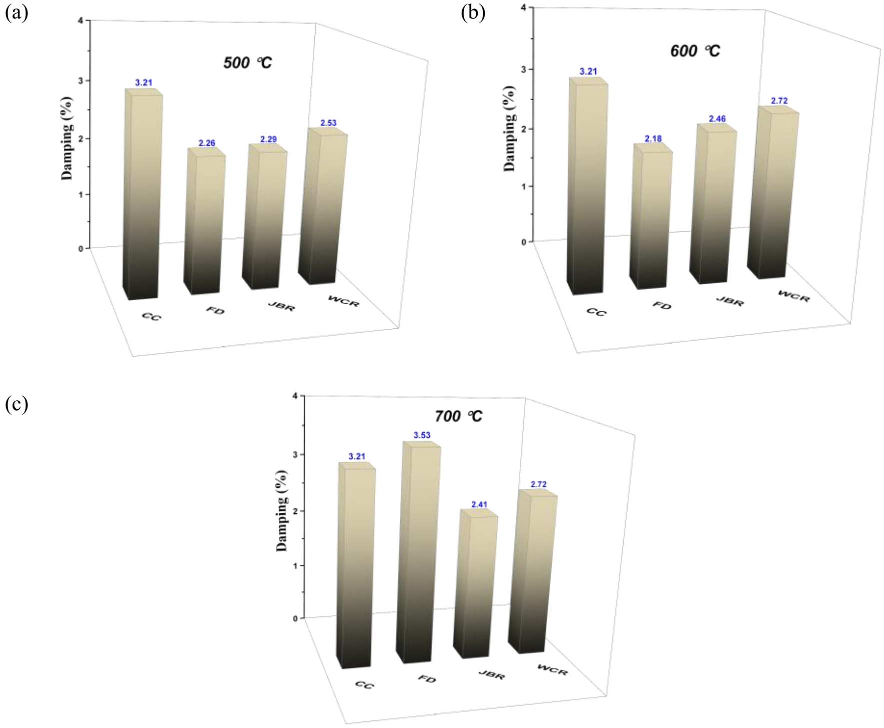

Fig. 8. Comparison of Damping of cylinders for different post fire curing techniques and exposed temperature, a) at 500°C, b) at 600°C, c) at 700°C.

3.5 Damping

Post fire variation in damping shows no observable relationship. In Fig.8 at temperature 500°C and 600°C damping of cylinders decreased from 3.21% to 2.26% and 2.18% respectively, this could be because of loss of stiffness, but at 700°C damping increased from 3.21% to 3.5%. For JBR and WCR methods damping showed same behavior. It was observed that damping was recovered using JBR and WCR techniques. For method JBR 500°C and 600°C cylinders recovered damping from 2.26% and 2.18% to 2.29% and 2.46%, while for WCR damping was regained to 2.53% and 2.72% compared to post fire cylinder damping. For 700°C where temperature exposure led to abrupt increase in damping, damping was normalized from 3.5% to 2.8% for JBR and for WCR normalized to 2.86% from 3.5%. Although the behavior of damping of cylinders after fire exposure show variations but it is noted that after using WCR and JBR methods damping can be normalized.

4 Conclusions

This study presents a novel approach to post-fire curing, utilizing the JBR (jute bag curing repair) method for the strength recovery of concrete. For comparison, the effectiveness of this new method is evaluated against the traditional WCR (water tank curing repair) method, with results compared to both undamaged control concrete and specimens exposed to high temperatures (100°C-700°C). Mechanical and dynamic properties of the cylinders are thoroughly examined to evaluate the effectiveness of the proposed post-fire curing repair technique. Based on the obtained results, the conclusions are as follows.

1. The observed correlation between weight loss in cylinders and increasing temperature, ranging from 1.5% at 100°C to 6.8% at 700°C, is attributed to moisture evaporation within the concrete under elevated temperatures.
2. Compressive strength reductions, varying from 4% to over 90%, demonstrate the severe impact of temperature on concrete. The post-fire residual compressive strength, achieved through both the WCR and JBR methods, despite the latter displaying slightly lower values, highlights effectiveness in restoring compressive strength. For instance, the residual strength ratio can be increased from approximately 0.1 for the WCR case to 0.43 and to 0.30 for the JBR case.
3. In case of Ultrasonic pulse velocities, cylinders exposed to temperatures up to 300°C exhibited minor damage repair. In comparison, the JBR technique demonstrated damage repair percentages of 22%, 36%, 31%, and 30% at 400°C, 500°C, 600°C, and 700°C, respectively. The damage repair percentages utilizing the WCR method were 26%, 37%, 49%, and 62%.
4. The natural frequencies of cylinders exhibit a decrement with increasing temperatures, experiencing a notable reduction of 61% at 700°C.However, post-fire curing results in frequency recovery. For instance, at 700°C, the frequency of FD cylinders was 8.96 Hz, which increased to 10.68 Hz with WCR and 9.51 Hz with JBR.

5. Damping behaviors at 500°C and 600°C were similar; however, at 700°C, the damping of FD exhibited an increase to 3.53% compared to the control condition (CC) at 3.21%. Post-fire curing normalized the damping to 2.81% for JBR and 2.72% for WCR.
6. In summary, despite a slightly lower strength and dynamic recovery compared to the WCR technique, the newly introduced post-fire JBR method demonstrates practical potential for enhancing the mechanical and dynamic properties of fire-damaged concrete structures. The JBR proves to be a practical and effective post-fire curing method.

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