

THERMAL PERFORMANCE AND MECHANICAL PROPERTY ENHANCEMENT OF NYLON–GLASS HYBRID FIBER-REINFORCED CONCRETE

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ABSTRACT

This work analyses the mechanical behaviour of concrete reinforced with hybrid – nylon and glass – fibres under normal and thermal loads. Four concrete mixture proportions were proportioned with a constant water–cement (w/c) ratio of 0.45: a mix without fibers and 3 mixes with different proportions of nylon and glass fiber (0.25%N+0.75%G, 0.50%N+0.50%G and 0.75%N+0.25%G by volume of cement). Compressive, split tensile, and flexural strength tests were performed on all the samples at 28 and 90 days. In order to mimic thermal exposure, for the second case a 100°C constant temperature was assigned and mechanical tests were performed after cooling. The results indicate that the mechanical properties are improved in all aspects when hybrid fiber addition is adopted, in relation to the control mix. The performance enhancement was most promising for the blend containing 0.5%N and 0.5%G, showing up to 54% in compressive strength, 20% in tensile strength and 25% increase in flexural strength after 28 days of ambient curing. All mixes displayed a slight decrease in strength -5%-7%-after hot conditions but maintained better performance than the control. Interestingly, the 90-day results also indicated, that the thermal stabilizing effect of long time curing was inferior to some extent. The results confirm the fact that the presence of nylon–glass hybrid fiber reinforcement is effective not only in enhancing the early and long-term behavior of concrete but also in providing a fair resistance against moderate thermal attack. This enables it to be a viable option for high temperature or thermal cycling exposed structures..

Keywords: *Hybrid fiber reinforced concrete (HFRC), Thermal exposure, Glass fiber, Nylon fiber.*

1. INTRODUCTION

Concrete is the most widely used construction material. It has low tensile strength that leads to post tensile cracks that leads to corrosion of reinforcement. But both concrete and reinforced bars tend to lose strength under fire and high temperature. High temperature due to fire leads to disintegration of the cement gels. While organic and inorganic synthetic fiber deals with the problem resulting from low tensile strength of the concrete, it has some drawbacks (ASTM E119, 2014). But performance in fire is less than desirable for most fiber reinforced concrete. For example, synthetic fiber like nylon evaporates at around 100-200 degree Celsius and creates pores in the concrete. So expanded vapor under fire can escape without causing significant damage to microstructure (A. Chandramauli et al., 2018). So, fibers are needed to be tested for heat loss and overheating of a building.

Nylon Fiber has been used for delaying development rate of cracks, controlling width of cracks, arresting propagation of post tensile cracks of concrete structures (M. Perez-Pena and B. Mobasher, 1994). It is chemically inert as like other inorganic synthetic fibers but has a lower melting point of 200° C (Vagholkar, 2016). So, its usage along under moderate thermal cycling or under extreme elevated temperature under fire needs to be tested.

Fiber glass is relatively a new fiber. Glass fiber is extremely fine, lightweight and chemically inert. It can reduce shrinkage cracking and they are manufactured as continuous cylindrical filaments which can be cut into desired lengths (ASTM E119, 2000). This study builds upon the experimental program to assess the effect of moderate heating (100 °C) on the mechanical properties of nylon–glass hybrid fiber-reinforced concrete, using standardized test methods to determine compressive, split tensile, and flexural strength at 28 and 90 days. According to A. Paulmakesh et al., 2021, a glass fiber contains oxides with high heat and fire resistance and have an exceeding high melting point (8500c- 9000c). In recent years, a lot of studies have looked into how adding fibers affects the thermal properties of concrete. Compared to regular concrete, fiber-reinforced mixes tend to behave quite differently when it comes to heat. For example, Ozger et al., 2013, found that replacing part of the sand with nylon fibers (about 5,000 g/m³) increased the thermal conductivity by around 16% and the specific heat by about 50%. Similarly, Zhang et al., 2021, noticed that adding just 0.8% of short carbon or glass fibers (6 mm long, with a 0.5 water-to-cement ratio) boosted thermal conductivity by 14.3% and 12.7%, respectively. By the same study by Zhang et al., 2021, using 2% of polypropylene or basalt fibers (also 6 mm long) actually lowered thermal conductivity—by 13.2% for polypropylene and 7.8% for basalt. The type of fiber really makes a big difference in how concrete transfers and stores heat.

So, the key agenda for this research is the identification of these effects on concrete with different mix ratios of nylon-glass fibers up to 100 degree Celsius temperature.

2. METHODOLOGY

2.1 Specimen Preparation

The materials used in this study are Portland cement (CEM II/B-M), according to BDS EN 197-1:2003, strength class 42.5N, and tap water. The chemical composition of cement is given in Table 1 and physical and strength properties of cement is given in Table 2.

Table 1: Cement chemical composition

Compositions	C ₃ S	C ₂ S	C ₃ A	C ₄ AF	MgO	SO ₃	Free CaO
Unit (vol. %)	52.0	21.2	11.3	8.2	3.2	2.2	1.9

Table 2: Cement physical and strength properties

Specific Surface Area (m ² /kg)	Initial Setting Time (min)	Compressive Strength After 2 days (MPa)	Compressive Strength After 28 days (MPa)
392.4	176	14.0	45.0

Sylhet sand imported from local market was used as fine aggregate with a fraction up to 4mm to ensure no large debris or particles were present, ensuring angular grains and proper gradation. Gradation process conducted according to ASTM C33-93 and unit weights and void contents were calculated according to ASTM C29. Rodding method was used to calculate the unit weight. Specific gravity and absorption capacity were determined according to ASTM C127. Table 3 shows the properties of fine aggregates tested in the laboratory.

Table 3: Properties of fine aggregates

Properties	Apparent Specific Gravity	Bulk Specific Gravity (OD)	Bulk Specific Gravity (SSD)	Absorption Capacity (%)	Unit Weight (kg/m ³)	Moisture Content (%)	FM
Fine Aggregate	2.67	2.58	2.61	1.23	1516	3.82	3.11

Crushed stone aggregate was selected and used as coarse aggregate for its well graded nature. It was sources locally to maintain consistency and reliability in the concrete mix. The properties of coarse aggregates are presented in Table 4.

Table 4: Properties of coarse aggregates

Properties	Apparent Specific Gravity	Bulk Specific Gravity (OD)	Bulk Specific Gravity (SSD)	Absorption Capacity (%)	Unit Weight (kg/m ³)	Moisture Content (%)	FM
Coarse Aggregate	2.81	2.75	2.77	0.7	1610	1.1	6.83

The gradation curve obtained after sieve analysis of sand and coarse aggregate is presented in Figure 1

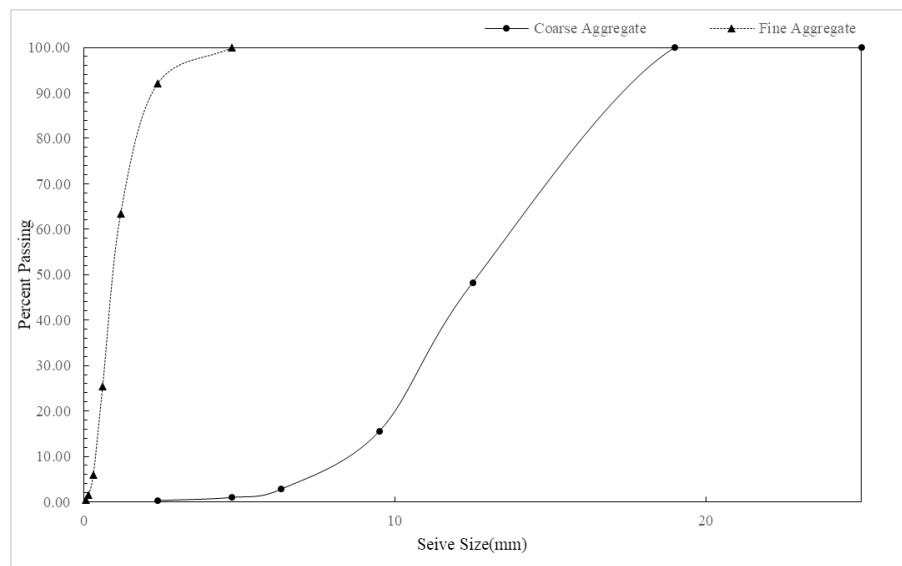


Figure 1: Gradation curve obtained of sand and coarse aggregate.

2.2 Nylon Fiber

Nylon fiber (NF) is obtained from 0.1mm diameter fishing fibers obtained from local market. It was cut into about $(2.00 \pm .25)$ inches) resulting in an approximated l/d ratio of 100. Table 5 shows the properties of tested fibers.

2.3 Glass Fiber

Glass fiber (GF) is obtained from glass fiber sheets from local markets imported from China. The glass fiber manufacturing process involved the flow of molten glass through heated sleeve plates of platinum alloy. The falling of sleeve plates dispersed glass into fine fibers and once after cooled. It was later sewed to glass sheets. The glass was approximately cut into (50 ± 5) mm length. The basic properties of tested fibers are presented in Table 5.

Table 5: Basic Properties of fibers

Type of Fiber	Average Thickness (μm)	Length (mm)	Tensile Strength (MPa)	Melting Point ($^{\circ}\text{C}$)
NF	250.0 ± 10.0	50.8 ± 6.35	800	250
GF	100.0 ± 10.0	50 ± 5	3500	850

2.4 Concrete Mixture Composition

Four different types of concrete mixtures (one without fibers or a base sample, and the rest with different percent compositions of hybrid glass nylon fibers) were produced for 28 days and 90 days testing. The total fiber content was 1.00% by volume of the cement. The base recipe (without fiber) was marked as BS. The 0.25% nylon and 0.75% glass sample were marked by 25N75G, 0.50% nylon and 0.50% glass sample were marked by 50N50G, 0.75% nylon and 0.25% glass sample were marked by 75N25G. To investigate the effect of fiber content on thermal properties additional twenty-four samples were produced. A constant w/c ratio of 0.45 was used for all mixtures.

3. METHODOLOGY

Currently there are no specific mix design guidelines available for Bangladesh using locally available materials. Even though ACI 211 and BS 812 are often used; achieving the required aggregate gradation such as ASTM C33 or BS 822 is challenging due to variations in local aggregate characteristics. A mix ration of 1:2:4 was used, consisting of 1 part cement, 2 part fine aggregate and 4 parts coarse aggregate by volume.

All the samples tested for 28 and 90 days were moist cured in lime water. For testing moderate heating effects, samples were heated in an oven dry machine with varying rate of heat increase. It took approximately 5-6 hours for the samples to be heated up to 100°C temperature. It was then cooled under air and tested when the samples were manageable and safe to be handled.

3.1 Slump Test

To evaluate workability of each mix variations, the slump test was conducted as per ASTM C143/C143 M. A slump cone was used and filled in three layers, each tamped 25 times with a standard rod to ensure uniform compaction. The reduction in height of concrete was measured to determine the slump value.

3.2 Compressive Strength Test

To assess the compressive strength properties of specimens, 100 mm diameter and 20mm in height cylindrical samples were meticulously prepared as per testing procedure followed ASTM C39 standards. Each sample specimen was placed carefully on the lower plate of the UTM (Universal Testing Machine) to ensure proper alignment with loading axis. A compressive load was then applied at a constant rate of loading at 2500N/sec (560 lb./sec) till failure occurred.

3.3 Split Tensile Strength Test

Cylindrical specimens with dimensions of 100 mm in diameter and 200 mm in height were cast specifically for split tensile strength test following ASTM (designation C496/C 496M) guidelines. A diametrical compressive force is applied continuously within a specified range of 0.7 to 1.4 M Pa/min without any sudden shocks. Tensile forces are induced on the plate containing the applied load but high compressive stresses are concentrated in the area immediately surrounding the load application point. The tensile failure occurs rather than compressive failure due to tri-axial compression state of the loaded areas that allows them to withstand a higher compressive stress compared to uniaxial compression tests.

3.4 Flexure Test

Specimen measuring 75mm x 75mm x 275mm were prepared and tested in accordance with ASTM C-78. To prevent immediate surface drying, which could potentially reduce the measured flexural strength, samples were tested immediately after removal from curing tanks. A deflection gauge was employed to measure mid span deflection with measurement taken up to L/150 of the beam span. Third point loading was employed to ensure applied forces were perpendicular to the face of the sample and no eccentricity were produced.

4. RESULTS AND DISCUSSIONS

4.1 Slump Test

The obtained slump value for 3 different hybrid groups and base samples are presented in Figure 2. While no admixtures are used, the obtained slump value is indicator of high water absorption of Glass Fiber.

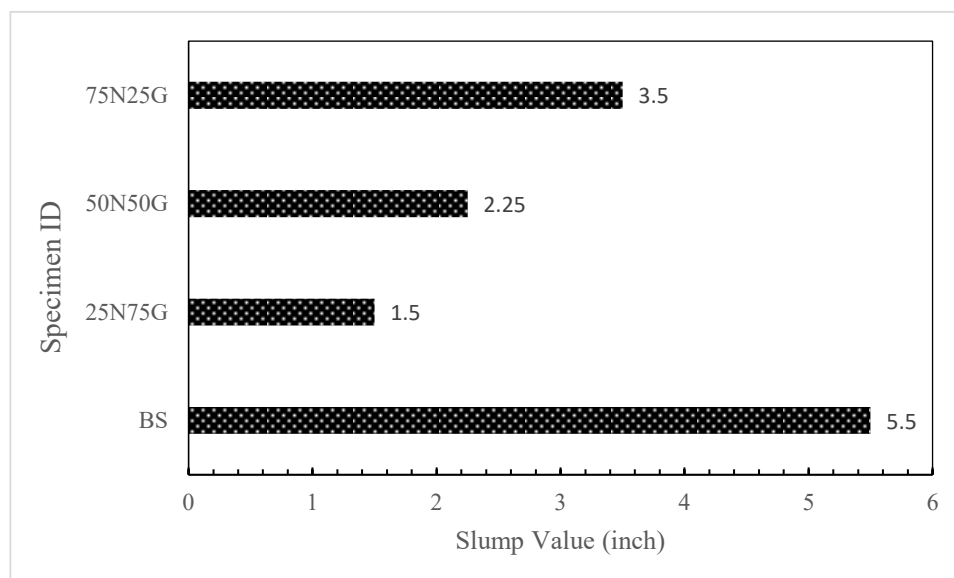


Figure 2: Slump Value of Nylon-Glass Fiber and Base Samples

The 25N75G sample resulted in a dry mix suitable for where only low workability is required. But the inclusion of admixtures can result in a workable mix. And the two other fiber samples were workable. For RCC (Reinforced Cement Concrete) beam and slabs, medium workability is adequate. Slump value between 2-4 inch indicates medium workability and the 50N50G and 25N75G sample is workable enough for normal constructions.

4.2 Compressive Strength Test

In order to determine the relationship between effect of fire on concrete structure with and without fiber, samples are tested for compressive stress and results obtained is presented below. Fire induces thermal expansion or tension stress which causes the spalling of the concrete. Adding fibers, particularly glass fibers, is an effective way to arrest crack propagation and check expansion of the concrete. The subsequent results of 28 days samples and 90 days samples after heated up to 100° C are presented in Table 6 and Figure 3(a, b).

Table 6: Compressive stress of samples before and after exposure to heat

Specimen ID	Compressive Strength (MPa)					
	28 days			90 days		
	Before Heating	After Heating	Percent Change (%)	Before Heating	After Heating	Percent Change (%)
BS	17	14	-17	20	17	-15
25N75G	32	31	-3.1	34	34	0
50N50G	34	33	-2.9	37	37	0
75N25G	31	30	-3.2	34	33	-2.9

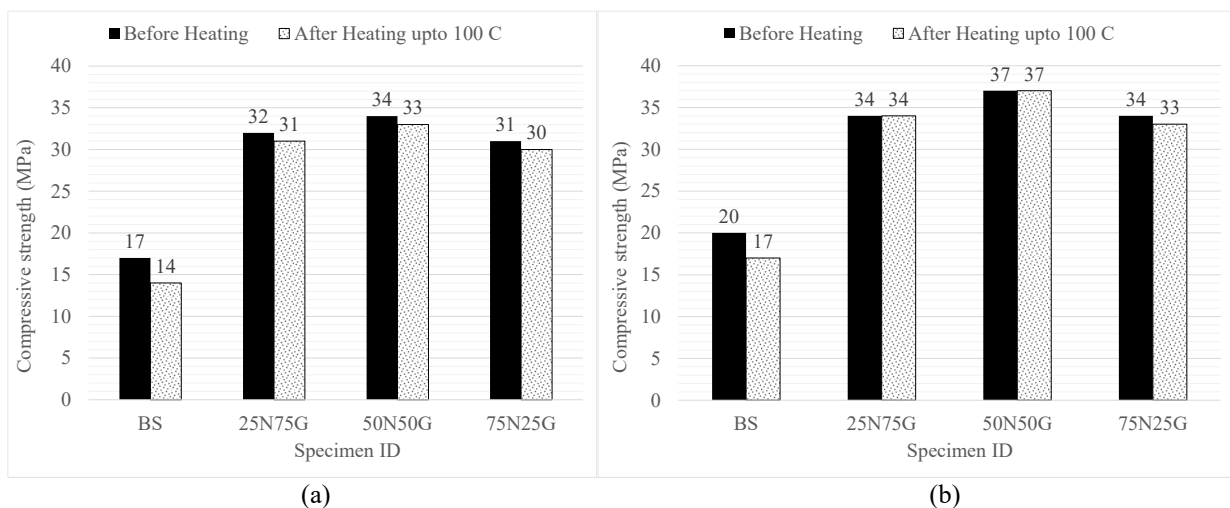


Figure 3: Compressive Strength (MPa) of specimens: (a)After 28 days; (b) After 90 days

The compressive strength is highest for 50N50G sample and but compressive strength drops when the increase of glass fiber is reduced or increased. So, the optimum mix must be around 0.5% glass and 0.5% nylon fiber mix. The glass fiber is covered by cement hydration products and strong adhesion between the GF and matrix. The distributed fiber mix restrains propagation of cracks, bridge cracks, delay development rate of cracks.

But increasing Glass Fiber content or Nylon Fiber with subsequent decrease in other fiber yields lower compressive stress values. When Glass Fiber content is increased interfacial bonding between cement matrix and fiber is decreased as there is less cement content in the matrix. So, the Glass fiber

cannot produce frictional stress via bonding of the cement. And when Nylon Fiber content is increased, the lower elastic modulus of Nylon Fiber as compared to Glass Fiber decreases the effective stiffness of composite cement matrix paste. Higher percentage of Nylon Fiber tend to clump together often creating a heterogenous mix of weak spots. Thus, increasing Nylon percentage yeids in lower compressive value.

But the effect of moderate heating upto 100 degree Celsius is best restrained when glass fiber content is 0.50% to 0.75%. For long term, 90 days testing, Compressive strength doesnot change for 25N75G and 50N50G samples. But the base concrete sample losed 17 percent of its compressive stress once heated upto 100° Celsius. Once Nylon is heated it undergoes thermal shrinkage and the fiber tends to be softer and weaker but Glass Fiber can withstand upto 850 degree Celsius and moderate heating can barely affect it.

4.3 Split Tensile Strength Test

While the effect of heat on the compressive stress of specimens were minimal, after exposure to heat, split tensile strength reduced significantly. The obtained values are presented in Table 7 and Figure 4.

Table 7: Split Tensile Stress of samples before and after exposure to heat

Specimen ID	Tensile Strength (MPa)					
	28 days			90 days		
	Before Heating	After Heating	Percent Change (%)	Before Heating	After Heating	Percent Change (%)
BS	3	2.7	-10	3.1	2.8	-9.7
25N75G	3.2	3.1	-3.2	3.9	3.7	-5.1
50N50G	3.8	3.5	-7.9	4.4	3.8	-8.2
75N25G	2.6	2.2	-15.4	3	2.5	-16.7

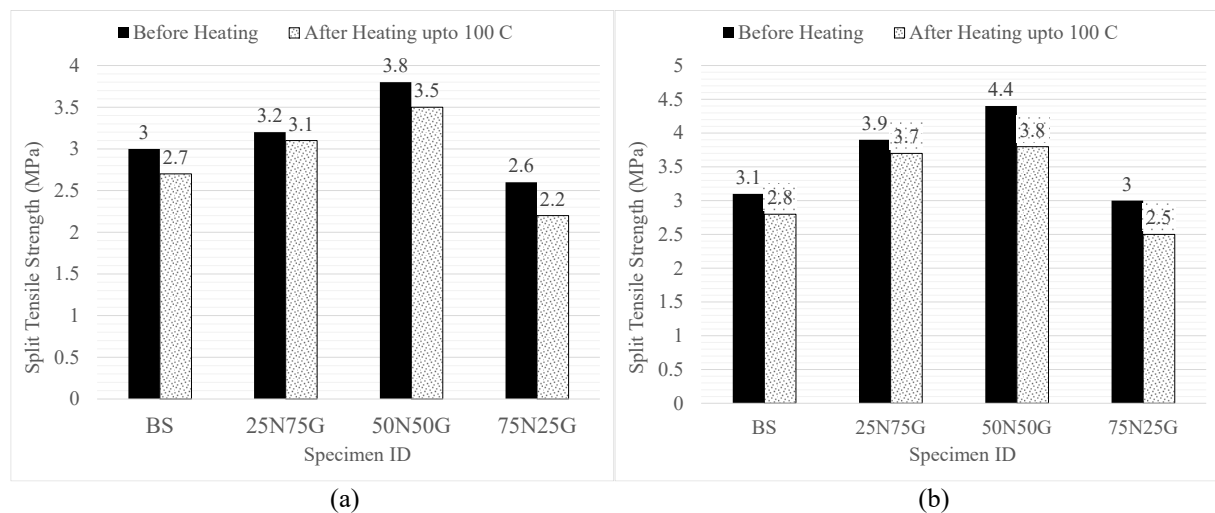


Figure 4: Split Tensile Strength(Mpa) of specimens (a) After 28 days; (b) After 90 days

Inorganic synthetic fiber is commonly used for increasing split tensile strength, resisting crack propagation and reducing development rate of cracks. The result is evident in normal conditions but unlike compressive strength, 0.75% Nylon Fiber and 0.25% Glass Fiber mix produces unexpected result. Split Tensile Strength is almost same as Base Sample mix.

But once heated, 50N50G sample produces significantly better tensile strength but it loses almost 7.9 and 8.2 percent of its tensile strength when tested for 28 and 90 days. So, if a structure is under fire the heating will exceed beyond 100 degree Celsius and susequent heat loss will yield a lower tensile strength.

Under moderate heating, 25N75G sample loses 3.1% and 5.1% of its tensile strength, indicating this mix might perform better and lose less tensile strength under extreme heating condition and making it suitable choice for catastrophic conditions. Nylon Fiber has a melting point at 200° C but once past 80-90° C, Nylon Fiber goes thermal shrinkage, softens, weakens and loses it 15-20% of tensile strength making it undesirable choice for moderate and unlikely choice for extreme heating conditions.

4.4 Flexural Stress Test

Flexural Stress is tested for samples of 28 days specimens and the obtained data is presented in Table 8.

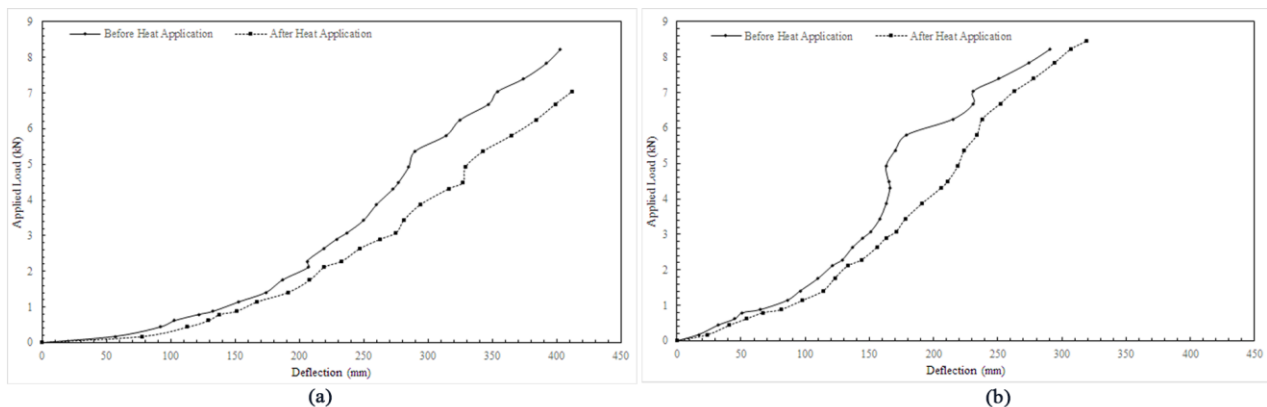
Table 8: Flexural Stress Test of samples for 28 days specimen before heating and after heating

Specimen ID	Flexural Strength (MPa)		Percent Change (%)
	Before Heating	After Heating	
BS	1.39	1.19	-14.4
25N75G	1.72	1.63	-5.2
50N50G	1.8	1.68	-6.7
75N25G	1.59	1.47	-7.5

The maximum flexural strength was obtained for 50N50G specimen. But like split tensile strength, percent loss was minimum for 25N75G sample and when 0.25% Nylon and 0.75% Glass Fiber was used in the mix. For extreme thermal condition and under fire the 25N75G sample or a sample that has higher Glass Fiber content is expected to perform better. 50N50G sample (1.80 MPa) has a 0.08 MPa more flexural strength than 25N75G sample (1.72 MPa) but under elevated temperature the difference reduces to 0.05 MPa. Higher Nylon content up to 0.5% may exhibit best flexural stress property under normal conditions but under elevated conditions, the higher proportion of Nylon Fiber exhibits higher percent loss of flexural stress.

4.5 Toughness

Toughness was calculated according to flexural data and formulated equations in ASTM C-1609. The load deflected curve of base sample and 3 different hybrid group before and after application of heat is presented in Figure 5. All the specimens used for flexural testing were samples from 28 days.



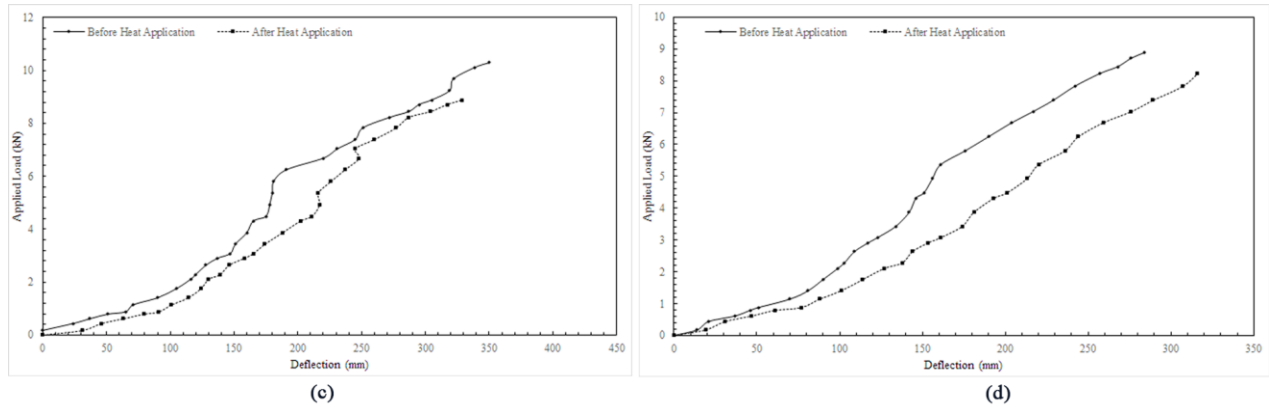


Figure 5: Applied Load vs Deflection curve of specimens before application of heat and after application of heat up to 100°C (a) Base Sample; (b) 25N75G; (c) 50N50G; (d) 75N25G

The toughness and energy absorption of each specimen, as calculated from area under the curve, is presented in Table 9.

Table 9: Flexural toughness of specimens before and after application of heat

Specimen ID	Toughness (J)		Percent Change (%)
	Before Heating	After Heating 100° C	
BS	1.66	1.48	-10.8
25N75G	1.56	1.45	-7.0
50N50G	2.7	1.56	-42.2
75N25G	1.81	1.61	-11.0

From the results, it's clear that heating the samples to 100°C reduced the toughness of all mixes. The load–deflection curves before and after heating show the same general shape, but the post-heating curves drop a bit, meaning the specimens couldn't absorb as much energy after cracking.

The base sample lost 10.8% toughness, which makes sense because heat causes small internal cracks and dries the material. Among the fiber mixes, 25N75G lost 7% energy absorption capacity. This suggests that having more glass fiber helps the concrete stay stable under heat.

While the 50N50G sample showed higher energy absorption as expected but once heated the sample has reduced its energy absorption capacity to 42.2 percent which is an anomaly. The significant cause of this exception may be due to choosing an aberrant sample to be recorded and plotting it in the curve. And the reason needs further research and investigation to be explained as by using SEM to figure out distribution property of fibers.

Yet, the 50N50G sample shows the most energy absorption capacity and has the highest toughness.

5. CONCLUSIONS

This study showed that adding a hybrid mix of nylon and glass fibers improves the overall performance of concrete, especially when the structure is exposed to moderate heat around 100°C.

- For compressive strength, the 50N50G mix performed the best under normal conditions. However, mixes with higher glass fiber content (25N75G and 50N50G) kept their strength more effectively after heating, while the base mix lost the most strength.

- Split tensile strength dropped for all samples after heating, but the 25N75G mix showed the lowest percentage loss. This suggests that concrete with more glass fiber can handle temperature-induced cracking better than mixes with more nylon.
- Flexural strength results followed a similar trend. The 50N50G sample had the highest flexural strength before heating, but the 25N75G mix again showed better stability and lower strength loss after heating.
- Toughness results confirmed that heating reduces energy absorption in all mixes. The 25N75G mix had the smallest drop in toughness, while 50N50G showed unexpectedly high loss after heating, indicating the need for further investigation into fiber distribution and we have to include microstructural analysis such as SEM to better understand fiber distribution, bonding quality, and why certain mixes behave unexpectedly under heat.

Based on all test results, using around 0.75% glass fiber and 0.25% nylon fiber appears to be the most balanced and heat-resistant option for practical applications.

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