**Experimental Studies on the Strength and Deformation Properties of Prestressed Concrete Columns Reinforced with Composite Polymer Rebar**

Barkhayot Akhmedov1, a), Lola Usmankhodjaeva1, b), Karomat Shukurova 1, c) and Makhliya Utegenova1, d)

1*Tashkent University of Architecture and Civil Engineering, 9 Yangi Shahar Street, Tashkent 100011, Uzbekistan*

*a) Corresponding author:* [*b.b.akhmedov24@gmail.com*](mailto:b.b.akhmedov24@gmail.com) *b)* [*lolausmanxodjayeva68@gmail.com*](mailto:lolausmanxodjayeva68@gmail.com) *c)* [*kshukurova035@gmail.com*](mailto:kshukurova035@gmail.com) *d) mahliyautegenova@gmail.com*

**Abstract.** This study compares the strength, stiffness, and crack resistance of prestressed concrete columns reinforced with steel versus composite polymer rebar under short‑term loading, with the goal of determining whether composite polymer reinforcement can serve as a viable alternative to steel reinforcement. The short‑term load tests on the composite‑reinforced prestressed columns were performed in accordance with current regulatory standards. The investigation showed that, under loading, the stress–strain behavior of composite‑reinforced prestressed columns-including crack initiation, propagation, and widening, the evolution of tensile and compressive strains, the growth of deflections, the attainment of limit states, and failure modes-closely mirrors that of columns reinforced with conventional steel. Replacing imported, high‑cost steel rebar with locally produced composite polymer reinforcement in prestressed concrete columns could yield substantial material savings and enhance the economic efficiency of the construction sector.

**Keywords:** composite polymer rebar, reinforcement, reinforced concrete, prestressed, basalt composite rebar, composite polymer reinforcement, deformation

# INTRODUCTION

# Composite polymer rebar (CPR) is not only a cost-effective alternative to steel reinforcement but also an innovative construction material that can yield positive outcomes unachievable with traditional steel reinforcement.

# Replacing steel reinforcement in reinforced concrete structures with high-strength, corrosion-resistant CPR is a current and pressing challenge. Despite its lower modulus of elasticity and reduced elongation compared to steel rebar, the use of CPR in prestressed structures has proven to be effective. However, CPR has low compressive strength and is considered a brittle material along the fiber direction, which complicates its application in the production of prestressed structural elements.

# METHODS

# To determine the reliability of the anchoring system used with CPR, both theoretical and experimental approaches were employed. Theoretical studies were based on general principles of structural mechanics, while practical investigations utilized methods for determining the mechanical properties of reinforcement according to State Standard 31938-2022 [1], and tests of prestressed concrete columns were conducted in accordance with the requirements of Urban Planning Norms and Regulations (UPNR) 2.03.14-18 [2], followed by comparison of the obtained results.

**Methods and Program of Experimental Research**

# The purpose of the tests was to manufacture prestressed concrete columns subjected to static loading, reinforced with both CPR and high-strength wire reinforcement WR1400 using an anchoring system, and to assess the columns' strength and crack resistance. Experimental laboratory studies were conducted at the accredited research and testing laboratory of BETOMAX BETON LLC, located in the Bektemir district of Tashkent. A detailed testing program was developed for these investigations.

# A total of 12 experimental column specimens were manufactured for static load testing, along with concrete cubes measuring 100×100×100 mm for auxiliary evaluations.

**Concrete Type Used in the Experiments**

# Heavy concrete was used in the experimental studies.

# The 12 specified columns are grouped into three sets of pairs.

The first pair of columns is reinforced mm with composite polymer rebar (CPR), while the second pair is reinforced with high-strength wire reinforcement WR1400. In all concrete columns, the level of prestressing was kept consistent, taking into account the tensile strength characteristics of the respective reinforcement types. The main properties of the tested column specimens are presented in Figure 1 and Table 1 [6].

# 

# FIGURE 1. Overview of the testing program by column type

High-strength wire reinforcement WR1400 and 5 mm diameter basalt composite rebar (BCR) were used as the main reinforcement in the concrete columns.

According to Clause 7 of the regulatory document [2], which outlines the applications of composite polymer reinforcement (CPR), and considering the fact that prestressed structures reinforced with CPR are neither manufactured nor commonly used in our country, it is essential to ensure human safety when implementing such structures.

Therefore, based on the research objectives, it is necessary to carefully select the type, geometric dimensions of the test columns, as well as the feasibility of their production and testing.

# A total of six prestressed concrete columns were fabricated for each type, with geometric dimensions of 100×100×2800 mm. In these columns, the main reinforcement is placed centrally and consists of either wire reinforcement WR1400 or composite BCR with a diameter of Ø5 mm.

**TABLE 1.** Main properties of the experimental columns

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Specimen series No.** | **Column specimen code** | **Concrete strength, MPa** | | | **Reinforcement ratio, %** | **σfp/Rfn** | **Reinforcement ratio, %** | **Residual stress in reinforcement, MPa** | |
| **Rbp** | **R** | **Rb** | **σfp** | **σfp(1)** | **σfp(2)** |
| 1 | BCR.5.28.StI - 1 | 26,0 | 33,5 | 29,2 | 0,196 | 0,704 | 1064 | 946 | 905 |
| BCR.5.28.StI - 2 | 26,2 | 33,4 | 28,9 | 0,196 | 0,704 | 1064 | 946 | 905 |
| BCR.5.28.StII - 1 | 26,1 | 33,6 | 29,0 | 0,196 | 0,704 | 1064 | 946 | 905 |
| BCR.5.28.StII - 2 | 26,0 | 33,5 | 29,2 | 0,196 | 0,704 | 1064 | 946 | 905 |
| BCR.5.28.StIII - 1 | 25,9 | 33,2 | 28,8 | 0,196 | 0,704 | 1064 | 946 | 905 |
| BCR.5.28StIII - 2 | 26,3 | 33,1 | 29,4 | 0,196 | 0,704 | 1064 | 946 | 905 |
| 2 | WR1400.5.28.StI - 1 | 26,5 | 33,7 | 28,8 | 0,196 | 0,702 | 1176 | 1023 | 943 |
| WR1400.5.28. StI - 2 | 26,2 | 33,3 | 29,1 | 0,196 | 0,702 | 1176 | 1023 | 943 |
| WR1400.5.28. StII - 1 | 26,5 | 33,1 | 29,6 | 0,196 | 0,702 | 1176 | 1023 | 943 |
| WR1400.5.28. StII - 2 | 26,3 | 33,0 | 28,9 | 0,196 | 0,702 | 1176 | 1023 | 943 |
| WR1400.5.28. StIII - 1 | 26,0 | 33,2 | 29,6 | 0,196 | 0,702 | 1176 | 1023 | 943 |
| WR1400.5.28StIII - 2 | 26,1 | 33,7 | 29,1 | 0,196 | 0,702 | 1176 | 1023 | 943 |

Local raw materials were used for the production of the experimental prestressed concrete columns. According to preliminary data, the following mix composition was used to produce 1 m³ of concrete (Table 2).

**TABLE 2.** Mix composition of heavy concrete selected for the experimental studies

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Concrete type | Material consumption per 1 m³ of concrete | | | | | |
| Cement, kg | Sand, kg | Aggregate | | W/C | Chemical additives (% of water) |
| 5-10 мм | 10-20 мм |
| Heavy Concrete | 460 | 595 | 455 | 670 | 0,5 | 0,45% |

The main reinforcement used consisted of wire reinforcement of class WR1400 with a diameter of Ø5 mm, centrally placed, and basalt composite reinforcement (BCR). Experimental values reflecting the properties of the reinforcement used are presented in Figures 2 and 3 [8].

|  |  |
| --- | --- |
|  |  |

# FIGURE 2. Results of Stress Loss Measurements in Prestressed Reinforcements Used for Column Manufacture

Initial stress value indicated by the pressure gauge;

Parameter for measuring residual stress in the reinforcement;

# Theoretical calculated value

**TABLE 3.** Properties of Reinforcement Used in the Fabrication of Concrete Columns

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Reinforcement grade | Diameter d, mm | Tensile strength limit Rf.n, MPa | Ultimate strength Rf, MPa | Elastic modulus Ef.n × 10³, MPa |
| BCR | 5 | 1430 | 1520 | 62,5 |
| WR1400 | 5 | 1480 | 1680 | 212,3 |

**Manufacture of Experimental Column Samples and Testing Methods**

# For the fabrication of experimental samples, a linear production line with a width of 1200 mm and length of 60 m was utilized. This line specializes in the production of prestressed multi-hollow slabs using the formwork-free technology of LLC "BETOMAX BETON," located in the Bektemir district of Tashkent city. One of the supports of this line is fixed, while the other support is movable, designed to release stresses in the anchoring device after the reinforced concrete element is completed.

# On the same production line, two separate wooden formworks are equipped for manufacturing two types of concrete columns. To prevent deformation along the length, shape changes, and slippage, and to ensure uniform dimensions during concrete work, the wooden formworks are temporarily fixed on immovable supports on both sides.

# The tensioning of the composite polymer reinforcement (CPR) was carried out using a manually operated pumping station in accordance with State Standard 7348 [3], while the tensioning of the steel wire reinforcement was performed using a hydraulic jack MIBATEC "Export" 350/S, also conforming to State Standard 7348 [3, 7]. The stress values induced in the reinforcement during tensioning were monitored using a pressure gauge and by measuring deformations in the reinforcement (Fig. 3).

# 

# FIGURE 3. Laboratory tensile stress-strain diagram for BCR and steel wire reinforcement, diameter 5 mm

# 1 – Composite polymer reinforcement with basalt fiber (BCR);

# 2 – Steel wire reinforcement class WR1400

The transverse force values, stresses in the reinforcement, as well as their losses, were measured using the DO-MG4 device in accordance with State Standard 22362 [4]. These data are based on determining the correlation between the hydraulic jack pulling force.

To measure the longitudinal relative strains in the reinforcement used in the fabrication of the columns, a metal ring with a threaded pitch of 300 mm was installed along the center of the total column length. Dial gauges with 0.01 mm accuracy were mounted on the metal ring. These gauges allowed the determination of additional strains occurring in the reinforcement of the prestressed columns. During installation of the metal rings and gauges, care was taken to avoid damage to the reinforcement surface, as mechanical damage could cause inaccuracies in strain measurements on the reinforcement surface.

The concrete was mixed using a forced-action mixer, and the same mix batch was used for casting two different columns. During concreting, vibration was performed manually. To determine the strength and deformative properties of the concrete simultaneously with column casting, control cubes measuring 100×100×100 mm were fabricated in accordance with State Standard 10180 [5]. The fabricated columns and cube specimens were cured for 28 days under natural conditions at a temperature of 20±2°C.

After concreting was completed, thermal treatment of the concrete columns began, maintaining and controlling a uniform surface temperature of the concrete columns within the formwork. The thermal treatment of concrete products at production facilities is typically standardized at a temperature of 80 ± 2°C. However, the strength of composite polymer reinforcement (CPR) decreases at temperatures above 60°C. This means that thermal treatment of concrete products reinforced with CPR requires additional time at production facilities, which in turn increases the cost of the product. Depending on the design strength of the CPR, the following coefficients accounting for working conditions during thermal treatment are recommended: 60°C – 0.9; 70°C – 0.85; 80°C – 0.8 [6].

Considering the above, to reduce the negative effect of thermal treatment temperature on the strength of reinforcement in concrete columns reinforced with BCR and VR1400, the thermal treatment temperature was set at 50°C. Thermal treatment of the concrete columns was carried out for 14 hours at this selected temperature (Fig. 4). After completing thermal treatment and before transferring stresses to the concrete at the supports, concrete strength was assessed using a non-destructive method according to State Standard 22690 [5] with the UKS-MG4 device. The difference between initial stresses during reinforcement relaxation and other effects was determined using the DO-MG4 device. Stress transfer to the concrete at the support was performed at concrete strength of 38–42 MPa (Fig. 5).

Metal elements located on the lateral parts of the columns (mid-span) had dial gauges attached to the reinforcement at 300 mm intervals (Fig. 5). Transfer of compressive stresses from the reinforcement to the concrete was conducted in   
4–5 stages, with intervals of 10–15 minutes between stages.

During tension transfer, stress values in the reinforcement were measured using dial gauges and jack manometers installed on each rod. At the same time, longitudinal strains in the reinforcement, average strain values in the upper part of the concrete, and lengths of the anchored reinforcement zones were recorded.

After completing the prestressing, specimens were placed on racks and observed until the concrete reached the required strength without any applied load. During this observation period, decreases in prestress were measured due to external load absence, increases in elasticity, and deformation caused by concrete shrinkage and creep.

# Measurements (dynamometer readings, visual observation, and recording of crack initiation, crack width, and deflections) were taken twice at each stage—both during loading and unloading.

# 

# FIGURE 4. Thermal Treatment of Concrete

# 

# FIGURE 5. Measurement and transfer of residual stresses in BCR and WR1400 wires to concrete

# Testing of the experimental columns under static loads was carried out according to the scheme shown in Fig. 6. The load was applied horizontally by tensioning at a distance of 1000 mm from the support. The load magnitude was controlled using a dynamometer.

# 

# FIGURE 6. Testing scheme of columns for strength and crack resistance

# The extent of crack development throughout the cross-section of the columns was established for all load levels. At the normal cross-section in the bending zone at the reinforcement level, crack widths of 2–3 cracks were measured using a MPB-2 microscope with 24× magnification. After the columns failed, photographs were taken of the concrete protective layer, the dimensions of the cross-section, as well as the failure mode, crack widths, and their locations.

**Crack Resistance and Deformations of Prestressed Concrete Columns**

# During the testing of the columns, the moment of crack initiation was recorded both through visual observation and with the aid of a 24× magnification microscope. This was further refined by analyzing deformation curves of the compressed and tensioned zones of the concrete, the tensioned reinforcement, and the deflection of the element. In the tests, the first transverse cracks appeared in the bending zones—specifically in the cantilevered parts of the columns around the fixed hinge areas of the secondary supports. At each stage, the applied forces were monitored using a dynamometer. Cracks forming in the tension zones of the columns were marked with a marker and numbered. The emergence of cracks in the column specimens during the experimental investigations was determined relative to deformation values in the concrete and reinforcement.

# Simultaneously, the lateral surfaces of the columns were carefully observed. With this combined approach and at relatively low load levels (~0.1F\_ult), it was possible to identify the load stage at which cracks began to form.

# During the testing of the prestressed column specimens, the initial cracks in columns reinforced with basalt composite rebar (BCR) were recorded at moments ranging from 0.484 to 0.506, while in columns reinforced with WR1400 wire reinforcement, crack initiation moments ranged from 0.403 to 0.478. The moments of crack formation from a theoretical standpoint were determined by the following formula (1), considering the influence of prestressing on the concrete properties:

# (1)

# In all tested columns, vertical cracks initially appeared in the bending zones. As the loads increased, inclined cracks developed between the support and the load application point relative to the longitudinal axis.

# When loading the column specimens at a distance of 1 m from the hinged support, the onset of crushing in the compressed zones adjacent to the support was observed at ultimate load values between 0.56 and 0.72 of the column specimens in areas close to the loaded support. This process, occurring in the compressed zone of the concrete column, can be described as having relatively high resistance to tensile forces generated during the specimen testing.

# From the experimental studies, the relationships between crack widths and the ultimate bending moments in the concrete were recorded for each reinforcement type as follows:

# In specimens I, II, and III reinforced with BCR, cracks appeared at bending moments ranging from 0.83 to 1.01 kNm. In this case, the ratio of the crack-initiating moment to the ultimate moment was: =0,434

# In specimens I, II, and III reinforced with WR1400 wire reinforcement, vertical cracks appeared at bending moments between 0.69 and 0.88 kNm. The corresponding ratio of crack-initiating moment to ultimate moment was: =0,376

# During loading, at certain stages (from the second and subsequent stages), one or two initial vertical cracks appeared in the bending zones of the columns. As the load increased, additional vertical cracks formed. The width of the initial cracks was between 0.05 and 0.08 mm. With increasing loads, the vertical cracks widened, their tips rose along the height of the cross-section, and the crack width also increased. At loads approximately equal to half of the ultimate loads, the crack widths reached 0.12–0.2 mm. Further load increases led to intensive development and widening of the vertical cracks. When the ratio of the applied loads at various stages to the ultimate load was between 0.6 and 0.85, the crack widths reached values of 0.25–0.3 mm (see Fig. 7).

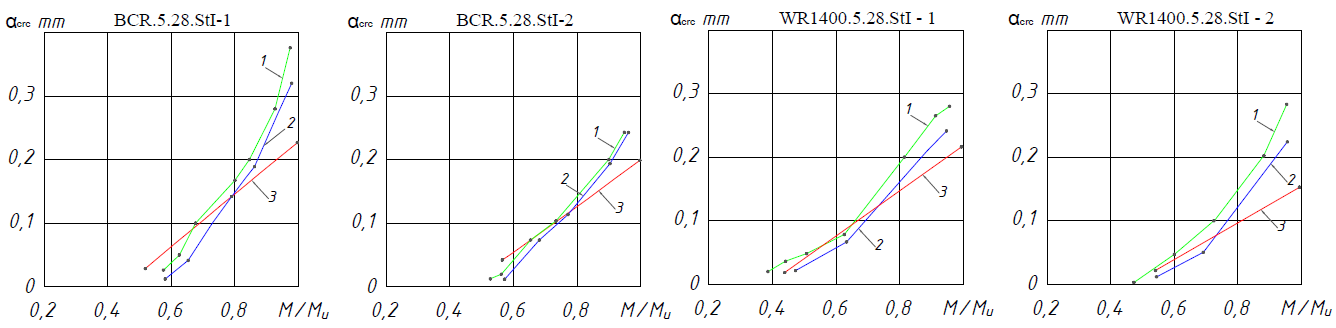
# 

# FIGURE 7. Observation and Measurement of Crack Formation in Columns under Loading

# RESULTS AND DISCUSSIONS

According to theoretical calculations, the moment values were 0.586 kN·m for basalt composite rebar (BCR) and 0.595 kN·m for WR1400 wire reinforcement. The average ratio of the laboratory-measured value to the calculated (theoretical) value was 1.56 for columns reinforced with BCR and 1.32 for columns reinforced with WR1400 wire reinforcement.

The test results showed that the deformations of the columns did not exceed the permissible limit values specified in the standards (see Fig. 8).



**FIGURE 8.** Crack Width in Specimens of the First Pair of Columns [6].

1 – Maximum laboratory values; 2 – Average laboratory values; 3 – Maximum values according to Construction Norms and Regulations (CNR) 2.03.01-24

The test results showed that cracks appear in columns reinforced with basalt composite rebar (BCR) when loaded with forces exceeding the design loads by 41.63%, whereas for columns reinforced with steel wire reinforcement WR1400, cracks appear at 15.96% above the design loads.

As the load increases in the tensile zone of the concrete in the columns, the first cracks appear when the tensile stresses reach the calculated tensile strength of the concrete. From this moment onward, the stress-strain state in the column specimens changes qualitatively, showing a redistribution of stresses between the concrete and the reinforcement. After the formation of the first cracks, the tensile zone almost completely loses its resistance, and the concrete and reinforcement work together only in the concrete areas between the cracks.

The experimental results were compared with theoretical calculations in accordance with the regulatory document [2]. The comparison of the theoretical moments calculated according to Urban Planning Norms and Regulations (UPNR) 2.03.14 [2] with the moments at which actual cracks formed showed that the laboratory moments for many specimens exceeded the theoretical values; in some cases, this difference reached 41.9%. Moreover, at high load levels, it was observed that prestressed concrete columns reinforced with BCR had a load-bearing capacity 15.38% higher and exhibited crack widths 14.77% slower to develop compared to prestressed concrete columns reinforced with steel wire reinforcement. Nevertheless, at certain loads exceeding the theoretical design values, BCR-reinforced concrete columns experienced sudden failure.

Considering that BCR-reinforced concrete columns may fail abruptly under load and taking into account the requirements for seismic and fire safety of buildings and structures, as well as human life safety, their temporary use in load-bearing structural elements (such as columns and beams) is not recommended until further studies address unresolved issues in this area.

# CONCLUSION

It has been established that the characteristics of the stress-strain state arising under load, including the formation, development, and propagation of cracks, deformation evolution in longitudinally compressed and tensioned zones, accumulation of strains in elements, the onset of ultimate states, as well as the mode and characteristics of failure, are similar in prestressed columns reinforced with basalt composite rebar (BCR) and those reinforced with wire reinforcement.

An increase in deflections of the column specimens was observed in accordance with the rising load levels. It was determined that the deflection values obtained experimentally and those calculated theoretically were consistent.

It is necessary to control the temperature during the heat treatment process of structures reinforced with composite polymer reinforcement (CPR). The influence of temperature variation during the heat treatment of prestressed concrete columns on the mechanical properties of CPR was studied. Based on the results, the optimal temperature for the heat treatment of CPR-reinforced structures is considered to be 500°C.

It is recommended to design and calculate prestressed concrete columns reinforced with CPR according to ultimate limit states, similarly to prestressed concrete columns reinforced with steel wire reinforcement. At the same time, it is advisable to introduce appropriate modifications accounting for the specific characteristics of CPR from a structural engineering perspective. When using composite reinforcement, the corresponding concrete classes should also be specified.

# REFERENCES

1. State Standard 31938–2022, Composite polymer rebar for concrete reinforcement: General technical specifications (Gvozdev Research Institute of Concrete and Reinforced Concrete (NIIZhB), Moscow, 2022).
2. UPNR 2.03.14–18, Concrete structures reinforced with composite polymer rebar (State Committee for Architecture and Construction of the Republic of Uzbekistan, Tashkent, 2018).
3. State Standard 7348–81, Carbon steel wire for reinforcement of prestressed reinforced concrete structures: Technical specifications (Standards Publishing, Moscow, 1981).
4. State Standard 22362–77, Reinforced concrete structures: Methods for measuring prestressing force in reinforcement (Standartinform, Moscow, 1977).
5. State Standard 10180–2012, Concrete: Methods for determining compressive strength based on control samples (Standartinform, Moscow, 2018).
6. B. B. Akhmedov, Development of anchorage devices for the tensile testing of composite rebar and stress transfer in prestressed concrete structures, PhD dissertation (Tashkent Institute of Architecture and Civil Engineering, Tashkent, 2023).
7. B. B. Akhmedov, Architecture Construction Design **4**, 147 (2021).
8. B. B. Akhmedov, in Proc. Int. Conf. on Innovative Development of Education, Tashkent, Uzbekistan, June 15, 2022 (Innovative Academy, Tashkent, 2022), pp. 315–324.