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STUDY OF POLYMER COMPOSITE REINFORCEMENT

ПОЛИМЕРЛІК КОМПОЗИТТІК НЫҒАЙТУДЫ ЗЕРТТЕУ

ИССЛЕДОВАНИЕ ПОЛИМЕРНОЙ КОМПОЗИТНОЙ АРМАТУРЫ

Abstract. *The article discusses the features of the use of cement concrete with polymer composite reinforcement (PKA) in building structures. The relevance of the study is due to the need to increase the corrosion resistance and durability of reinforced concrete elements, especially in aggressive environments. The aim of the work is to study the adhesion of advanced control systems of various profiles to cement concrete under the influence of operational and technological factors. Within the framework of the study, literature sources on this topic were analyzed, as well as experimental tests of the adhesion strength of reinforcement to concrete after the influence of various factors: heat and humidity treatment, alternate freezing and thawing, water saturation, as well as the action of alkaline solutions. The effect of the concrete class on the efficiency of interaction with the PKA was studied. Features of fracture in the contact zone are revealed and the optimal type of reinforcing profile is determined. The work is of interest to designers and specialists in the field of development of new building materials and technologies.*
Keywords: *rebar adhesion strength, polymer composite rebar, carbon fiber bars, rebar diaameter, anchoring length.*

Аңдатпа. *Мақалада құрылыс конструкцияларында полимерлі композиттік арматурасы (ПКА) бар цемент-бетонды қолдану ерекшеліктері талқыланады. Зерттеудің өзектілігі, әсіресе, агрессивті ортада темірбетон элементтерінің коррозияға төзімділігі мен беріктігін арттыру қажеттілігіне байланысты. Жұмыстың мақсаты пайдалану және технологиялық факторлардың әсерінен бетонды цементтеу үшін әртүрлі бейіндегі алдыңғы қатарлы басқару жүйелерін желімдеуді зерттеу болып табылады. Зерттеу шеңберінде осы тақырыптағы әдебиет көздері талданып, әр түрлі факторлар: жылу мен ылғалдылықты өңдеу, кезектесіп қату және еріту, судың қанығуы, сондай-ақ сілті ерітінділерінің әрекеті әсерінен темір бетонға желім беріктігінің эксперименттік сынақтары жүргізілді. Бетон класының ПКА-мен өзара әрекеттесу тиімділігіне әсері зерттелді. Байланыс аймағындағы сыну ерекшеліктері анықталады және күшейтетін профильдің оңтайлы түрі анықталады. Бұл жұмыс дизайнерлер мен жаңа құрылыс материалдары мен технологияларын әзірлеу саласындағы мамандардың қызығушылығын тудырады.*
Түйін сөздер: *арматураның желім беріктігі, полимерлі композитті арматура, көміртекті талшықты торлар, арматура диаметрі, зәкір ұзындығы.*

Аннотация. *В статье рассматриваются особенности использования цементного бетона с полимеркомпозитной арматурой (ПКА) в строительных конструкциях. Актуальность исследования* *обусловлена необходимостью повышения коррозионной стойкости и долговечности армированных бетонных элементов, особенно в агрессивных средах. Целью работы является исследование сцепления ПКА различного профиля с цементным бетоном в условиях воздействия эксплуатационных и технологических факторов. В рамках исследования проанализированы литературные источники по данной тематике, а также проведены экспериментальные испытания прочности сцепления арматуры с бетоном после воздействия различных факторов: тепло-влажностной обработки, попеременного замораживания и оттаивания, водонасыщения, а также действия щелочных растворов. Изучено влияние класса бетона на эффективность взаимодействия с ПКА. Выявлены особенности разрушения в контактной зоне и определён оптимальный тип арматурного профиля. Работа представляет интерес для проектировщиков и специалистов в области разработки новых строительных материалов и технологий.*

Ключевые слова: *прочность сцепления арматуры, полимер композитная арматура, углепластиковые стержни, диааметр арматуры, длина анкеровки.*

Introduction. In recent years, there has been an active introduction of polymer composite materials into the construction industry, in particular, polymer composite reinforcement (PCA), which is positioned as an alternative to traditional steel reinforcement. The main reason for the growing interest in this type of rebar is its high performance characteristics: corrosion resistance, durability, low weight, resistance to chemical effects and temperature extremes.

The use of PKA in construction has received regulatory support: a number of interstate standards have been approved that regulate the production and use of this material (GOST 31938-2012, GOST 32486-2013, GOST 32487-2013, GOST 32492-2013). In the Republic of Kazakhstan, the right to use polymer reinforcement in reinforced concrete structures is enshrined in Technical Regulation No1198 «Safety Requirements for Reinforced Concrete, Concrete Structures» dated December 22, 2008, where paragraph 89 for the first time fixes the possibility of its use for construction purposes.

Among the advantages of PKA are the following: inertness to aggressive environments, low thermal conductivity, linear expansion coefficient close to concrete, dielectric properties, radio transparency, resistance to electromagnetic radiation, environmental safety and service life of at least 80 years. It is also important that the PCA has a much lower weight compared to steel reinforcement, which reduces transportation costs and simplifies the installation process.

Despite the obvious advantages, the widespread use of PKA requires a comprehensive assessment of its interaction with the concrete matrix in various operating conditions. This determines the relevance of this study aimed at analyzing the strength characteristics of the «concrete-PKA» contact zone, taking into account the factors affecting the adhesion, strength and reliability of reinforced structures.

Literature review. Polymer composite reinforcement (PCA), including glass, basalt, and carbon fiber bars, is widely used in reinforced concrete structures as an alternative to steel reinforcement. However, the peculiarities of the interaction between PCA and the concrete matrix require in-depth study, especially under various loads and environmental conditions.

As established in a number of works, the adhesion of the PCA to concrete increases with a decrease in the diameter of the reinforcement. This is due to the uneven distribution of stresses across the bar cross-section caused by its complex composite structure, as well as the Poisson effect (Yılmaz & Alptekin, 2018; Holschemacher & Weiße, 2016). However, in concretes with a compressive strength of more than 50 MPa, this dependence is leveled.

According to the increase in the length of the anchorage, the average shear stresses of the coupling decrease, which is due to their nonlinear distribution along the length of the contact. When more than 20 diameters of reinforcement are embedded, the growth of adhesion practically stops. This is confirmed by both the direct tearing method and the beam method (Di Bella et al., 2020; El-Shafie et al., 2019).

The strength of concrete has a direct impact on the amount of adhesion of the PCA, especially during a direct breakout. However, with a concrete strength of more than 30–40 MPa, this effect is reduced, which is explained by the destruction of the composite rod on the surface of the epoxy layer (Pavlík & Černý, 2015).

The work showed that reducing the thickness of the protective layer leads to a decrease in adhesion. When using fiberglass reinforcement with a diameter of 8 mm, the adhesion difference between the samples with a protective layer of 30 mm and 15 mm was 10-15% (Borisov, 2004).

Experiments have shown a decrease in adhesion after holding in water at a temperature of +60 °C and thermal cycling. The reduction in grip strength ranged from 2 to 19%, depending on the profile and conditions. At the same time, it is noted that such results contradict the data obtained in the Belelyubsky Mechanical Laboratory (Garkavi, 1995).

Separate tests of PCA in concrete grades M500 and M600 showed satisfactory adhesion values (43-58 kg/cm²), but prolonged exposure to a humid environment leads to degradation of the reinforcement surface, especially if E-glass is used (Golunov, 2003).

Mohamed (2021) conducted a study of the effect of cyclic freezing/thawing on the adhesion of SPA and BPA. It was found that after 100 cycles, adhesion increased, especially for UVA with a diameter of 10–12 mm, while after 200 cycles a decrease was observed. An increase in slippage at maximum stresses is also recorded for rebar with a smaller diameter.

At long-term loading, up to 50% of the maximum strain value of slippage has stabilized. With an increase in the load up to 75% and simultaneous exposure to moisture or an alkaline environment, premature destruction of the reinforcement and an increase in slippage were observed as early as 300-320 days (Slatvinskaya & Sviderksiy, 2014).

Katz (1995) showed a sharp decrease in the adhesion of the PCA to concrete at temperatures above 100 °C, which is associated with the transition of organic matrices to a plastic state above the glass transition temperature.

However, in the study by Kustikova (2018), preheating of the valves to +50 °C and subsequent thermal moisture treatment (isothermal mode 80 °C) led to an increase in adhesion by 5-10%.

The use of polymer composite rebar (PCA) abroad began in the 1960s and 70s, when the industrial production of fiberglass reinforcement was established in the United States. In the same period, the term «glass plastic concrete» appeared, reflecting the principle of reinforcement of concrete structures with PCA. Since then, composite rebar has been actively introduced into various areas of construction, especially where there was a high probability of aggressive environmental impact on traditional steel rebar.

The key impetus for the active development of PCA was the problems associated with the corrosion of steel reinforcement, especially in bridges and road structures. Studies by Boyle and Karbhari (1994) and Benmokrane et al. (1996) showed a significant reduction in the durability of structures when using even protected steel, which prompted engineers to look for alternatives.

One of the striking examples of foreign experience was the construction of a bridge on Uhlenbergstrasse in Düsseldorf (Germany), where prestressed fiberglass reinforcement was used for the first time. Similar innovations were implemented in Japan (Sumitomo), where composite materials based on aramid and carbon fibers were used in the supporting structures of bridges.

North American countries have also made a significant contribution to the development of PCA. In Canada, Pultrall developed V-ROD valves that have been used in a number of major infrastructure projects, including the I-65 bridge in Indiana. Such structures have shown high resistance to chlorides and aggressive environments, in particular in the upper layers of concrete slabs, where the risk of icing and the use of salts is especially high.

According to analysts, by 2017, the composite rebar market had grown 5 times compared to 2011, reaching a volume of $1.5 billion. The main consumer is the United States (about 40% of the world market), followed by Europe (29%) and Asia (24%). China is actively developing this area, establishing mass production of PCAs, including through popular trading platforms such as Alibaba.

The use of PCA is actively expanding to specialized structures, such as airfield pavements, facilities with high requirements for electromagnetic compatibility (e.g., tomographic rooms), electrolysis baths, reactors, and even structures of sea breakwaters. An example is the experimental section of the airfield in Kazan, where the PCA replaced steel reinforcement without losing operational characteristics.

In addition, studies and full-scale tests carried out in Russia (e.g., KSUAE together with PJSC Tatneft) confirmed that composite reinforcement can effectively replace steel in road slabs, beams, floor slabs, and other prefabricated elements. This indicates the high versatility and reliability of PCA in a wide range of construction applications.

At present, the main directions of development of PCA are to improve the characteristics of adhesion to concrete, increase alkali resistance, modulus of elasticity, and resistance to ultraviolet radiation. On the world market, there is a variety of types of PCA by type of fiber (glass, carbon, basalt), type of binder, geometry, and type of profile, which expands the possibilities of choosing reinforcement for specific tasks.

Materials and methods. In this study, polymer composite reinforcement (PKA) of various types, including fiberglass (SPA) and basalt plastic reinforcement (BPA), was used as a reinforcing element. The studies were carried out to assess the adhesion of the APC to the concrete matrix under various operating conditions, as well as to determine the influence of geometric and structural parameters on the anchoring efficiency.

Polymer composite rebar (PCA): Fiberglass rebar (SPA): made on the basis of glass roving and thermosetting epoxy matrix. The diameters of the test rods are 8 mm, 10 mm, 12 mm, 15.9 mm and 19.1 mm.

Basalt plastic rebar (BPA): was produced using basalt fiber and a similar polymer matrix.

The surface of the reinforcement had a winding (corrugation) or sand coating to improve adhesion to concrete.

Concrete mixtures with different design compressive strength were used: from B25 (M350) to B50 (M700).

The concrete mixture included: Portland cement M500, medium-sized sand, crushed stone fraction 5-20 mm and water. The V/C ratio ranged from 0.42 to 0.50.

To modify the concrete mixture, superplasticizers based on poly-carboxylates were used.

Two main methods were used to determine the adhesion strength of the spacecraft to concrete:

Direct tearing method: samples consisted of concrete cubes (150×150×150 mm in size), in which one vertically installed rod of the spacecraft was enclosed in the center. After 28 days of hardening, the reinforcement was drawn with a fixed displacement speed. The maximum breakout force was recorded, as well as the slippage of the reinforcement in the coupling zone.

Beam method: prismatic concrete samples with reinforcement buried in the tension zone were used. A load was applied to the free end of the reinforcement until the clutch was destroyed. The method made it possible to simulate the real working conditions of reinforcement in beam structures.

Tests under aggressive influences: the samples were kept in an aqueous environment, in water at a temperature of +60 °C, and also subjected to freeze-thaw cycles (up to 200 cycles) in the temperature range from -20 to +60 °C.

Tests were also carried out after holding the rebar in an alkaline solution (NaOH, pH>12) and under heat and humidity conditions.

Measurement of adhesion strength: The adhesion strength was calculated using the formula:

τ=Fmax π·d·l τ= π·d·l F max, where τ τ is the average shear of the clutch voltage, MPa; F max F Max is the maximum pullout force, N; d d is the diameter of the reinforcement, mm; l l is the length of embedding in concrete, mm.

Slippage Estimation: Stress-slippage plots based on linear inductive displacement sensors were used to analyze the deformation characteristics of the clutch.

Each series of experiments included at least 5 parallel samples. The results were processed statistically, with the calculation of mean values and standard deviations. The reliability of the differences was assessed using the Student's t-test at the significance level $\alpha = 0.05$.

Results and their discussion. The results of tests by the direct break-out method and the beam method showed that the adhesion of the PKA to concrete increases with a decrease in the diameter of the member. This is due to the uneven distribution of stresses in the cross-section of the composite reinforcement and the pronounced Poisson effect, especially with increased diameters. However, in high-strength concretes (more than 50 MPa), this effect is leveled, and the differences between the adhesion for PCA of different diameters become insignificant.

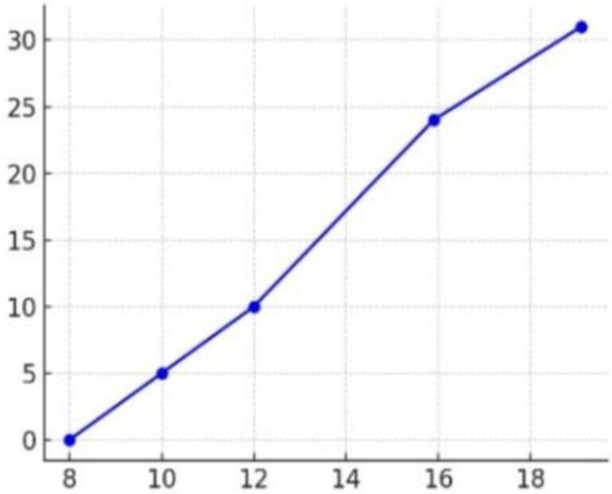

Figure 1. Diameter of PCA mm

Note – compiled by the author

Decrease in adhesion with an increase in the diameter of the PCA: it can be seen that with an increase in the diameter of the rod, the adhesion decreases, especially noticeable in the 15.9 and 19.1 mm rods.

Regardless of the test method, it has been found that as the length of the anchorage increases, there is a decrease in the average shear stresses of the adhesion. For example, for a PCA with a diameter of 15.9 mm, with an increase in the contact zone from 3d to 7d, the value of adhesion decreased to 62-83% of the initial value, and for rods with a diameter of 19.1 mm – to 68-71%. This is due to the non-linear distribution of forces along the length of the embedding. It is noteworthy that with an anchorage length of more than 20 diameters, the clutch stabilizes and does not change.

Effect of anchor length: Increasing the anchoring length reduces the mean shear stresses due to the redistribution of forces.

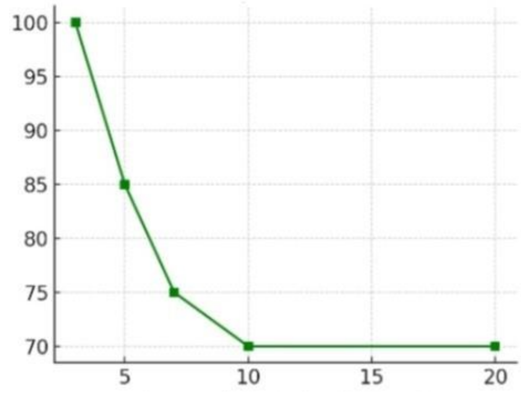

Figure 2. Name of figure

Note – compiled by the author

Studies have confirmed that an increase in the strength of concrete leads to an increase in adhesion to the RCA in an almost linear manner, especially in the case of the direct pull-out method. However, in the case of the beam method, the increase in adhesion is less pronounced. In some cases, for example, with a concrete strength of more than 40 MPa, destruction occurs not along the contact zone, but along a weak epoxy layer on the surface of the spacecraft, which limits further build-up of adhesion.

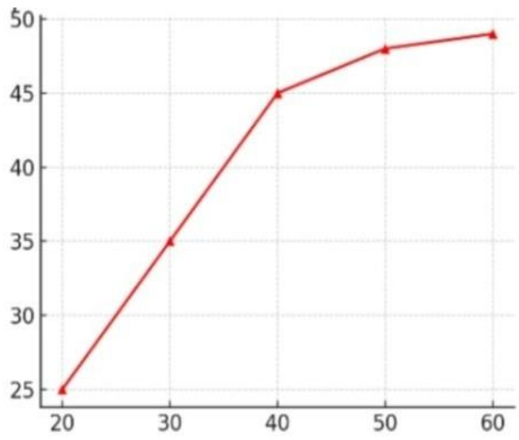

Figure 3. Concrete strength MPa

Note – compiled by the author

Concrete strength and adhesion: As the strength of concrete increases, the adhesion to the PKA increases, but the tendency weakens when the strength is above 50 MPa.

Tests have shown that reducing the protective layer of concrete from 30 mm to 15 mm leads to a decrease in adhesion by 10-15%. This is due to the concentration of stresses in the area of the near surface of the concrete and its possible delamination or cracking under load.

After holding the spacecraft in water and at a temperature of +60 °C for 90 days, a moderate decrease in adhesion by 2–9% was observed, depending on the type of spacecraft and profile. Thermocyclic tests (-20/+60 °C, 30 cycles) resulted in a 4-17% reduction in bond strength. At the same time, in a number of cases, there was even an increase in adhesion after exposure to an aggressive environment, which is explained by the redistribution of stresses and partial strengthening of the contact zone.

At long-term loading (350 days) at the level of 25–50% of the maximum force, no significant changes in the slippage value were observed. However, at 75% load and simultaneous exposure to moisture or alkaline solutions, increased slippage and premature destruction of the contact area were observed.

Studies by A. Katz (1999) showed a sharp decrease in adhesion at temperatures above 100 °C, which is associated with the destruction of the organic binder PKA when the glass transition temperature is exceeded. However, in other works, with short-term heating to +50 °C or with wet heat treatment (up to 80 °C), an increase in adhesion of 5–10% was noted, which is associated with improved adhesion between the matrix and the filler.

Conclusions. The study made it possible to obtain a holistic view of the nature of the adhesion of polymer composite reinforcement (PKA) with cement concrete. It has been established that, unlike steel reinforcement, the scope of research in this area remains limited, especially in domestic scientific practice, which does not allow to fully take into account the specific features of locally produced polymer reinforcement when designing reinforced concrete structures.

Comprehensive breakout tests made it possible to determine the relationship between the type of spacecraft and the nature of operation in the clutch zone. The most effective type of spacecraft with a sand coating has proven to be the most effective, providing high adhesion (up to 19 MPa) without significant slippage. Glued coiled rebar is characterized by lower breakout resistance (≈13.6–14.1 MPa) and greater slippage, which indicates a loss of grip already in the initial stages of loading.

Analysis of the impact of operational factors showed that temperature fluctuations significantly affect the clutch: high temperatures reduce it by almost half, while low temperatures increase it. An alkaline aggressive environment has a destructive effect on the strength of adhesion, especially for reinforcement with a sand coating. The influence of other factors, such as HME, water saturation and thermal cycles, was insignificant.

The dependence of the adhesion strength on the concrete class was also revealed: with an increase in the strength of concrete, the adhesion to the PKA increases non-linearly, but up to a certain limit, after which an increase in the strength of the concrete does not lead to a significant increase in adhesion due to the limitations associated with the characteristics of the polymer binder itself.

A cohesion model is proposed, taking into account three main components: adhesion, mechanical meshing and friction, each of which contributes to the overall resistance to the breakout of reinforcement from concrete. This approach makes it possible to more accurately describe and predict the behavior of reinforced concrete elements using PKA in various operating conditions.

Conflict of interest. The author(s) declare that there is no conflict of interest.

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Notice of the use of generative AI and AI-enabled technologies in the writing of the manuscrip. The author group did not use generative AI in the preparation of this article.

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