Experimental Study on the Mechanical Properties of Polyacrylonitrile Fiber Grout Material and Full Grout Sleeve Joints

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Abstract. In prefabricated concrete structures, the joints between the prefabricated components are crucial for the overall performance of the structure. However grout suffers from high brittleness and poor toughness. To enhance the mechanical connection performance of prefabricated structural joints, unidirectional pull-out tests were conducted on grout sleeve joint specimens with varying anchoring lengths, incorporating polyacrylonitrile (PAN) fibers into the grout material. The results show that, due to the 'bridging effect' of PAN fibers, the total tensile displacement of the joint specimens increases to varying degrees, and the extent of brittle failure is reduced. Additionally, as the anchoring length decreases, the addition of PAN fibers increases the strain value of the cylinder wall.

Keywords: Full grouting sleeve; Anchorage length; PAN fiber;

1 Introduction

Through standardized production and on-site assembly of components, prefabricated buildings have significantly improved production efficiency and have sparked a research surge in many countries[1].In prefabricated concrete structures, components are often joined using grout sleeves[2], with the reinforcement transmitting forces through the combined action of the grout material and the sleeve [3]. However, since the sleeve grouting material is a high-strength, early-strength mixed cement mortar, it exhibits brittleness. Under pressure, the test blocks often crush and fail, demonstrating very poor toughness. This brittleness is particularly problematic for unsaturated grouting joints, where the damage becomes especially severe when the steel bars are pulled out. This poses a significant challenge for prefabricated building nodes.

In the 1960s, Dr. Yu Zhanshu [4] of the United States invented a steel bar connection grouting sleeve, which fully proved the reliability of the connection technology after a large number of experimental studies. Subsequently, this technology was gradually introduced by various countries and has become a mature steel bar connection technology in the industrialization construction of European and American countrie. Yu Qiong [5]

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made 45 sleeve joint specimens for drawing experiments to study the failure forms of the joints and the influence laws of bond strength. Einea [6] designed connection specimens with different sleeve construction types and conducted unidirectional tensile tests. The results show that the tensile strength of the joint increases with the anchorage length of the reinforcement bar and the strength of the grouting material.Liu Xinyu [7] designed an analysis model with anchorage length and other test variables in order to study the factors affecting the grouting connection of high-strength sleeve of 500Mpa steel bar and used the finite element method for analysis. Ling [8] took the form of the sleeve, the buried length of the steel bar, and the diameter of the sleeve as variables, and then conducted a unidirectional stretching experiment until the specimen was damaged, revealing the factors that should be considered in the design of the grouting sleeve joint, and analyzing the performance of the connecting specimen. Seo [9] studied and analyzed the relationship between the bonding force and bearing capacity of the grouting material and steel bar inside the sleeve.

To enhance its toughness, this paper introduces polyacrylonitrile (PAN) fiber. The inclusion of PAN fiber enables the grout to undergo substantial deformation, improves its stress distribution, and increases the overall toughness of the grout. Additionally, it enhances the bonding and anchoring performance between the grout matrix, sleeve, and steel bars. This advancement is of significant importance for the performance of connections between fiber-reinforced grout and grout sleeves, as well as for the development of prefabricated buildings.

2 Experimental

2.1 Raw Materials

Grout material includes: common (JZ) grout with a water-to-material ratio of 0.11, polyacrylonitrile (PAN) fiber grouting material, two kinds of fiber length 6 mm, 9 mm, 4 kinds of content 0.5kg/m^3, 0.9kg/m^3, 1.3kg/m^3, 1.7kg/m^3. The performance indexes of PAN fiber are shown in the Table 1. The material parameters of the sleeve joint include: the diameter of the steel bar is 18 mm, which is HRB400 grade steel bar. The detailed parameters of the sleeve are shown in Figure 1.

Table 1. Polyacrylonitrile (PAN) fiber specific parameters

Tensile strength (MPa)	Elongation at break/%	Elastic modulus (GPa)	Density (g/cm3)	Diameter (um)
537	22	7.2	1.18	12

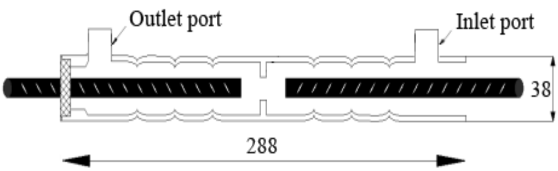


Fig. 1. Schematic diagram of sleeve structure and parameters

2.2 Test Programme

Grouting material mechanical properties test: The test methods for grouting material fluidity, compressive strength, and flexural strengthare conducted in accordance with the relevant codes. The basic and optimal fiber content grouting material and the grouting sleeve with anchorage lengths of 4d, 5d, 6d, 7d and 8d (d is the diameter of the steel bar) were selected to carry out the drawing test.

Sleeve joint test loading schem: The specimen is loaded at a force controlled uniform speed at a loading rate of 1 kN/s until the specimen is damaged. The test apparatus is shown in Figure 2. The wall strain and the end strain of the steel bar were collected by the static data acquisition instrument. The arrangement scheme of the strain gauge in the anchoring section is shown in Figure 3.

Fig. 2. Test apparatus

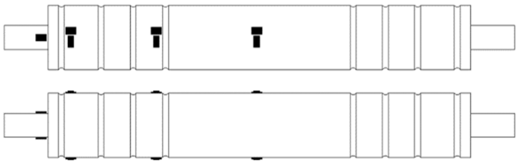


Fig. 3. Paste position attempt

3 Mechanical Property

3.1 The Fluidity of Grout

It can be seen from Figure 4 that the influence rules of polyacrylonitrile (PAN) fiber with different dosage and length on the initial flow and 30 min flow of grout are roughly similar. The larger the amount and length of fiber, the worse the initial flow and 30 min flow. The content of fiber has the greatest influence on the initial flow, followed by the length of fiber. When the fiber content is 0.5, the initial fluidity is basically unchanged compared with the base group. When the fiber content starts from 0.9 to the maximum content, the initial fluidity of each group is significantly reduced. Compared with the base group, the initial fluidity of the 6mm group is decreased by 2.1% to 25.5%, and that of the 12mm group is decreased by 4.8% to 19.3%. This is because the fiber is wrapped in liquid cementing material inside the slurry, and the existence of the fiber will affect the expansion of the fluidity, resulting in a decrease in its fluidity. At the same dosage, the fiber length increases and the resistance effect increases. As the number of fiber roots decreases, the resistance effect will be reduced, and the two effects will reduce each other, resulting in the flow of grouting material is not affected by the fiber length. At the same length, the larger the dosage, the more the number of fibers, the more the resistance effect on slurry flow increases, and the fluidity decreases.

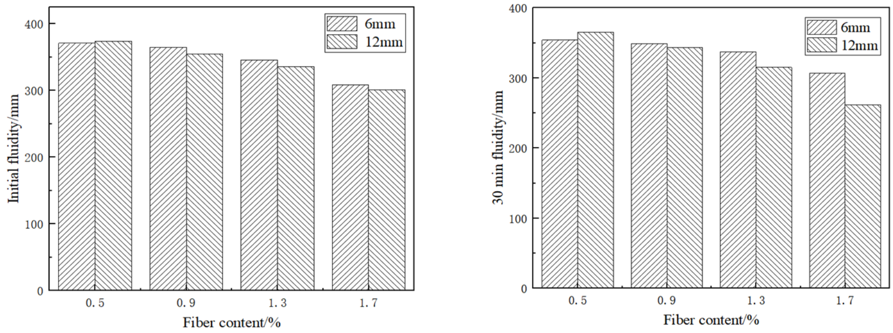


Fig. 4. Effect of length and dosage parameters of PP fibeon fluidity of grouting material

3.2 Strength Properties

As can be seen from the Table 2, no matter the fiber length is 6mm or 12mm,with the increase of the content of PAN fiber, the strength of 28 days presents a trend of first increasing and then decreasing .This is because after the PAN fiber is mixed into the grout, the fibers at the weak interface inside the grout and the micro-cracks play a bridging role. When the test block bears the load, the fibers can play a role in transferring the internal stress, making the internal force distribution more uniform, and preventing the further damage of the damaged interface.

When the dosage is appropriate, the effect is particularly significant, which is beneficial to strength. When the content exceeds the optimal value, with the increase of the content, due to the relatively large specific surface area of the fiber, and the density of the fiber itself is very small, it also has a good flexibility, and excessive PP fiber occupies a lot of space inside the grout, so that the inside of the slurry is not dense, so that the strength is reduced. Based on the above research and analysis of the mechanical properties of fiber, the optimal content and length of fiber were determined:0.5%and 6 mm, and the bonding and anchoring characteristics of the next part of sleeve joint were studied with this mix ratio.

Table 2. Flexural and compressive strength test results

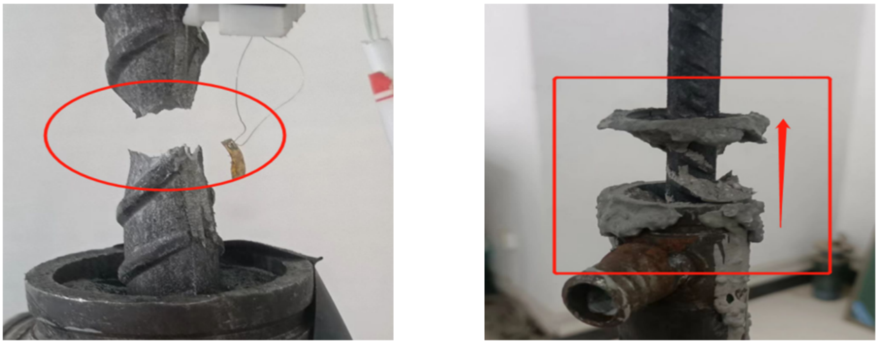
Specimen	flexural strength (MPa)			compressive strength (MPa)		
	1d	3d	28d	1d	3d	28
JZ	12.5	13.6	14.9	39.5	58.6	78.5
6-0.5	12.4	13.1	16.8	41.2	59.8	85.7
6-0.9	12.7	13.9	16.2	40.9	60.8	84.8
6-1.3	13.2	14.2	14.8	40.2	58.6	82.4
6-1.7	13.1	14.6	13.9	39.5	57.2	79.5
12-0.5	12.9	13.9	15.6	42.1	59.5	80.0
12-0.9	13.2	14.2	16.8	41.3	62.3	78.5
12-1.3	13.7	15.4	14.7	40.5	60.5	76.5
12-1.7	13.7	13.0	13.3	40.0	56.4	77.7

4 Test Result

4.1 Test Phenomenon

For the grout sleeve, there is a strong mechanical bite force between the sleeve and the grout material, and the bond between the two is good. In addition, the actual contact area between the sleeve and the slurry is much larger than the contact area between the steel bar and the slurry, and there is sufficient bonding capacity between the two. Therefore, the bond ability between reinforcement bar and grouting material is the key to study the bond anchorage performance of specimens. Two failure modes of steel bar breakage and steel bar pulling out appeared in the specimen, as shown in Figure 5.

The yield strength and ultimate bond strength of each specimen were obtained through the test, and the average value of the results of the three specimens was taken and the failure mode was observed, as shown in Table 3.



(a) Tensile failure of steel bar (b) Pull-out failure of steel bar

Fig. 5. Illustration of failure mode.

Table 3. Test results of the mechanical properties.

Specimen	Yield strength (MPa)	Ultimate strength (MPa)	Bond strength (MPa)	Failure mode
JZ-8d	447.5	610.6	>19.08	Bar fracture
JZ-7d	447.7	613.5	>21.91	Bar fracture
JZ-6d	449.0	613.3	>25.55	Bar fracture
JZ-5d	445.0	535.4	>26.77	Bar pull-out
JZ-4d	443.8	448.5	>28.03	Bar pull-out
6-0.5-8d	444.6	610.4	>19.08	Bar fracture
6-0.5-7d	452.5	616.1	>22.01	Bar fracture
6-0.5-6d	448.1	609.6	>25.40	Bar fracture
6-0.5-5d	447.4	577.7	>28.88	Bar pull-out
6-0.5-4d	446.0	553.2	>34.58	Bar pull-out

The anchoring performance is mainly affected by the anchoring length and grouting material. First, for the same grout sleeve joint specimen, the anchor of the steel bar. The solid length has a direct influence on the failure mode of the specimen. With the increase of anchorage length, the ultimate bearing capacity of the specimen increases, and the anchorage performance is better.

When the anchorage length of the steel bar is short, the bonding strength between the steel bar and the grout material is insufficient, leading to pull-out failure of the steel bar at the joint. As the anchorage length of the reinforcement increases, the mechanical interlocking force between the grout and the reinforcement becomes stronger. Consequently, the bond strength of the reinforcement with the grout surpasses that of the steel bar itself, which can lead to steel bar fracture.

4.2 Load-Displacement Curve

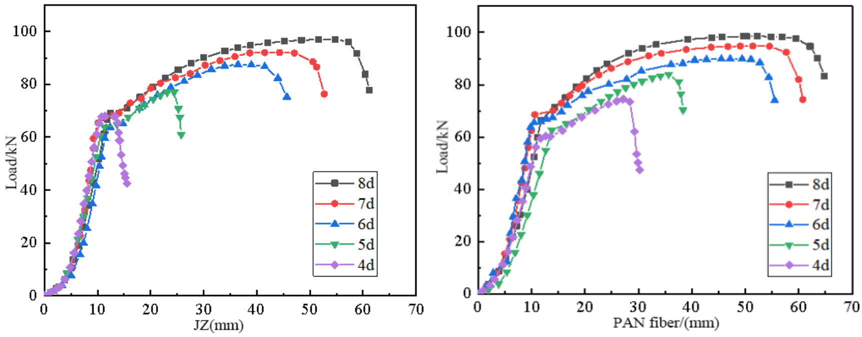


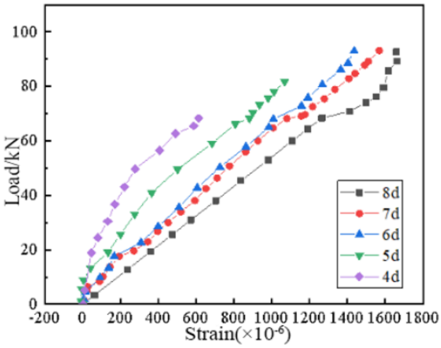
Fig. 6. Load-displacement curves of grouting material rebar sleeve connection specimens

As shown in Figure 6, at anchoring lengths of 8d, 7d, and 6d, both with and without polyacrylonitrile (PAN) fiber, the load-displacement curve exhibits distinct reinforcement and necking stages. The curve takes on an arc shape, and the observed surface failure mode is steel bar breakage.

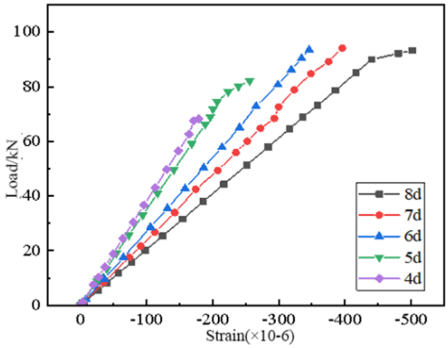
During the unidirectional drawing test, the total elongation for reinforcement anchorage lengths of 8d, 7d, 5d, and 4d shows that the total displacement of the fiber grouting sleeve joint is greater than that of the reference group grouting sleeve joint at the same anchorage length. As the anchorage length decreases, the displacement of the fiber grouting sleeve joint increases proportionally. Compared to the reference group, the total displacement of the fiber group increased by 5.9%, and by 86.54% at an anchorage length of 4d. However, at an anchorage length of 6d, the total displacement of the reference group exceeds that of the fiber group. This is because, at this length, the bonding strength between the reinforcement and the grout material, as well as the tensile strength of the reinforcement, nearly reaches their critical values simultaneously, leading to significant slip during the reinforcement pull-out process.

In terms of bond strength, the improvement is most pronounced at anchoring lengths of 5d and 4d. Compared with the control group, the strength of the polyacrylonitrile

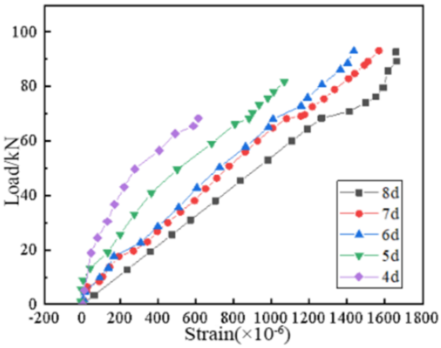
(PAN) fiber fiber group increased by 7.88% to 23.37%.. The presence of the fiber enhances the integrity of the grout matrix inside the sleeve, resulting in a more uniform distribution of forces. During the stretching process of the sleeve, the Poisson effect causes the sleeve to undergo transverse shrinkage. This leads to a grout matrix within the fiber grout sleeve joint that exhibits greater toughness and is less prone to crushing, thereby improving the bond strength between the reinforcement bar and the grout material. Consequently, this also enhances the ultimate strength of the sleeve joint.



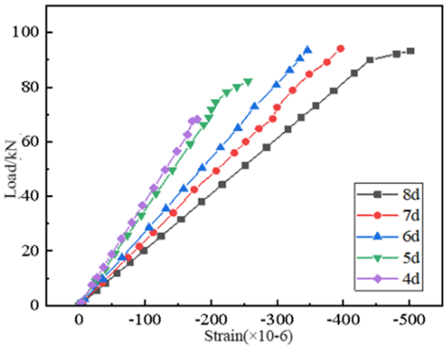
(a) Longitudinal load-strain curve of the PAN fiber group sleeve



(b) Transverse load-strain curve of PAN fiber group sleeve



(c) Longitudinal load-strain curve of the sleeve of the reference group



(d) Transverse load-strain curve of the reference group sleeve

Fig. 7. Load-strain curve at center position (Different anchor lengths)

4.3 Load-Strain Curve

When the polyacrylonitrile (PAN) fiber group is subjected to unidirectional tensile load, the longitudinal strain of the cylinder wall increases progressively with the applied load. For the groups with anchorage lengths of 8d, 7d, and 6d, the strain values decrease as the anchorage length decreases. Once the unidirectional tensile load reaches the yield point of the steel bar, the load no longer increases during the yield stage, and the strain value remains relatively stable. As the load continues to rise, the steel bar transitions into the strengthening and neck contraction stage, and the strain value of the cylinder wall essentially remains unchanged. However, for the groups with anchorage lengths of 5d and 4d, where the steel bars do not fracture, the strain value of the cylinder wall continues to increase steadily with the applied tensile load.

As shown in Figure 7, when the anchorage lengths are 8d, 7d, and 6d, the transverse strain of the polyacrylonitrile (PAN) fiber tube wall increases progressively with the unidirectional tensile load. For an anchorage length of 8d, when the load reaches the ultimate load of the steel bar, the load no longer increases, and the strain of the cylinder wall continues to rise,indicating that the steel bar has entered the strengthening and necking stage. For anchorage lengths of 5d and 4d, the anchorage length of the sleeve is insufficient, resulting in inadequate bond strength between the steel bar and the grout material. Consequently, the final failure mode is steel bar pull-out. During the unidirectional stretching process, the steel bar gradually slips within the grout sleeve, leading to a reduced strain value in the cylinder wall.

For the transverse strain value of the grout sleeve, the strain observed in the sleeve wall of the polyacrylonitrile (PAN) fiber group shows a noticeable increase compared to the base group across different anchorage lengths.

5 Conclusions

In this paper, the polyacrylonitrile (PAN) fiber is utilized to enhance the performance of the slurry. After determining the optimal fiber content and length,a unidirectional tensile test is conducted to examine its failure modes and load-displacement curves. The following conclusions are drawn.

1. The addition of polyacrylonitrile (PAN) fiber will reduce the fluidity of grout. The amount of PAN fiber has a great influence on the bending strength, while the length of PAN fiber has little influence on the bending strength. Taking fluidity, compressive strength and flexural strength as reference indexes, the optimal content and length of polyacrylonitrile (PAN) fiber were selected as 0.5%kg/m^3 and 6 mm.
2. The addition of polyacrylonitrile (PAN) fiber enhances the toughness of the grout matrix within the fiber grout sleeve joint, making it less prone to crushing. This improvement also increases the bond strength between the steel bar and the grout material, resulting in a higher ultimate strength of the sleeve joint.
3. Compared to the reference group, the fiber grout matrix exhibits greater uniformity and integrity due to the ‘bridging action’ of the polyacrylonitrile (PAN) fibers. Under the same anchorage length, the fiber-reinforced grout shows a larger displacement in the unidirectional tensile test. The inclusion of polyacrylonitrile (PAN) fibers effectively improves the failure mode and reduces the extent of brittle failure.

References

1. MARTINEZ S, JARDON A, NAVARRO J M, et al. (2008) Building industrialization: Robotized assembly of modular products[J]. Assembly Automation,2008,28(2):134-142,1-2.
2. GUO Zhengxing,YAN Wen.(2018)Experimental study on the fullness of grout connection grout of prefabricated concrete structure sleeve[J].Jiangsu Architecture,2018(3):4-8,2-5.(in chinese)
3. YEE A A.(1976)Prestressing concrete for buildings[J].Pci J-ournal,1976,21(5):112-157,6-7.
4. Zhang Youhai, LIU Xinghua, WU Weiping. (2014)Performance comparison of grouting materials for steel bar sleeve joint in prefabricated construction [J]. Concrete World, 2014,(11): 80-83,1-2.
5. YU Qiong, SUN Jiaqiu, YUAN Weihang. (2018)Experimental Study on bond behavior between ribbed steel bars and sleeve constrained grouting material[J]. Journal of Harbin Institute of Technology,2018,50(12):98-106(in Chinese),6-7.
6. Einea A,Yamane T,Tadros M K.(1995)Grout-filled pipe spli-ces for precast concrete construction[J].PCI Journal,1995,40(l):82-93,4-5.
7. Liu Xinyu, Zeng Sizhi, Zhu Chunhui, et al. (2022)Mechani-cal properties of high-strength sleeve grouting connec-tion based on 500 MPa steel bar[J].Journal of Nanc-hang University(Engineering Science),2022,44(04):335-343,2-8.(in chinese)
8. Ling J H,Rahman A B,Ibrahim I S,et al.(2016)Tensile capacity of grouted splice sleeves[J].Engineering Structures,2016,111:285-296,2-7.
9. SEO S Y, NAM B R, KIM S K.(2016)Tensile strength of the grout-filled head-splice-sleeve[J]. Construction and Building Materials,2016,124:155-166,2-4.