Performance of grouts for post-tensioned prestressed structures

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Abstract: New high performance grouts with high volume stability and good fluidity are prepared with Portland cement and a multifunctional admixture (MFA). The rheological characteristics and mechanical performance of the grouts are investigated. The addition of MFA effectively improves the pseudo-plasticity of the grout. The Ma cone flow time decreases obviously, and the bleeding rate tends to be zero. The deformation behaviors of fresh mixture and hardened grout are systematically studied. Mercury injection method (MIP), scanning electron microscopy (SEM) and X-ray diffractory analysis experiments are used to analyze the microstructure evolution of the grouts, which manifests that the co-action of the early bubble reaction and the latter ettringite crystallization ensure the volume stability throughout the whole hydration process and result in refined pore structure of the grout.

Key words: post-tensioned; cement; grout; deformation behavior; microstructure; admixture

Bonded post-tensioned prestressed structures have become increasingly popular in recent years due to their convenience of construction, high load capacity and economical benefit. As a major procedure of these types of structures, grouting will not only transfer prestressed force between the concrete and the prestressed tendons, but also protect prestressed tendons from the invasion of outside hazardous ions. The function of the grout should be ensured by its quality, i. e. volume stability as well as fluidity. Engineers have had to make great efforts to control the quality of the grout in the past years. Fine aluminum powder is widely used to improve the compaction degree of the grout injected into tendon ducts. However, the latter shrinkage due to the further cement hydration cannot be compensated by such methods. The danger of self-ignition and uncontrolled reaction rate also limit the use of aluminum. Superplastisizer is used in grout to achieve high fluidity. But the tradeoff is that it releases the free water and increases the bleeding rate greatly, which can cause unsettlement of the grout and fatal damage to the structures.

Schokker, et al. [1] prepared grouts with cement, fly ash and several separate admixtures and investigated the corrosion resistance of the grout. Kroggel, et al. [2] and Ashar, et al. [3] studied the inspection of the grout quality using ultrasound methods. There are limited papers concerned with the volume stability of the grout and the preparation of high performance grout with a multifunctional admixture[4,5].

In this paper, high performance grouts with compressive strengths of 40 to 65 MPa are prepared with Portland cement and a multifunctional admixture (MFA). The properties of the grout such as the fluidity, bleeding rate and mechanical performance are investigated. The deformational behavior of the grout is studied throughout the whole hydration process. Mercury injection method (MIP), X-ray diffractory analysis (XRD) and scanning electron microscopy (SEM) tests are utilized to study the microstructure evolution of the hardened grout.

1 Experiments

1.1 Materials

1) Cement Portland cement with GB standard 42.5 grade from Nanjing Jiangnan Cement Plant is used. The tested compressive strength of the cement at 28 d is 60 MPa according to GB/T 17671 — 1999. The chemical and physical properties of the cement are shown in Tab.1.

Tab.1 Chemical composition, density and specific surface area of cement

Chemical composition/%						Density/ $(kg \cdot m^{-3})$	Specific area/ $(m^2 \cdot kg^{-1})$
SiO_2	Al_2O_3	CaO	SO_3	MgO	Fe_2O_3		
22.06	5.13	64.37	2.03	1.06	5.25	3 150	308

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2) Admixtures An MFA is used in this research, which is developed especially for bonded post-tensioned prestressed grout by Jiangsu Bote New Materials Co., Ltd. It is mainly composed of superplasticizer, surface modified aluminum, expansive agent and a water-soluble polymer. The tested pH value of MFA is 7.0 and chloride ions content is 0.03%. A sulphonated naphthalene formaldehyde superplasticizer (SNF) is used for comparison.

1.2 Testing procedures

All tests are conducted at (20 ± 2) ℃.

1.2.1 Ma cone flow time

Ma cone flow time (see Fig. 1) is adopted to evaluate the rheological properties of the grout. Before testing, the bottom mouth is plugged up. Pour the fresh mixture into the cone to a certain volume (1 725 mL). Then open the bottom mouth and count time with a stopwatch. Record the time as soon as the flowing line of the mixture begins to show discontinuity. The tested Ma cone flow time of pure water is 7 to 8 s for the same volume.

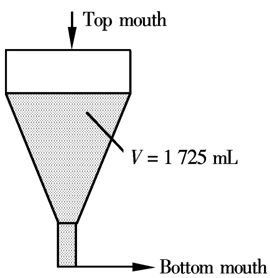

Fig.1 Setup of Ma cone flow time

1.2.2 Bleeding rate

Weigh a 100 mL graduate G_0, and pour the fresh mixture into the graduate to about 4/5 of its height and record the total weight G_1. After 0.5 h of placement, aspirate the clear water on the surface of the grout into a beaker with lid per hour, until no water can be aspirated in three successive times. Measure the volume of the clear water in the beaker V_w, the bleeding rate B_w can be calculated by the following equation:

$$B_w = \frac{V_w}{\frac{G_1 - G_0}{W}} \times 100\% \tag{1}$$

where W is the water percentage of the grout (by weight).

1.2.3 Volume change of young grout (before 24 h)

Inject 100 mL of the fresh grout mixture into a rubber bag, then extrude the bag and fasten it at the end with a steel wire. After that put the bag into a 250 mL plastic bottle. Then cover the bottle using a lid embedded with a 5 mL-graduated pipette. Infuse water into the bottle from the top of the pipette to a designed height and tight with a drop of liquid paraffin on the water surface. Record the change of the liquid height in the pipette beginning half an hour after the mixing of the water and the cement. Six samples are tested for each batch and the result is the averaged value.

1.2.4 Length change of hardened grout paste

Two batches of paste prisms with the size of 25 mm × 25 mm × 280 mm are prepared without vibration and demmoulded 24 h later. Firstly, the initial length is measured. Then, put one batch of specimens into water at (20 ± 2) ℃ for expansion measurement. The other batch is sealed with polyethylene membrane first and then self-adhesive aluminum foil outside for autogenous shrinkage measurement. A JDY-2 universal length lineal measure machine with precision of 1 μm is utilized for the length variation test.

1.2.5 Mechanical performance

Paste specimens with the size of 40 mm × 40 mm × 160 mm are tested for flexural strength first and then compressive strength. Moulds with the size of 100 mm × 100 mm × 200 mm and horizontally embedded with ϕ6 mm round steel bar at the center are employed for steel bar bond strength test. All these specimens are cast without vibration.

1.3 Mix proportion design

Five mix proportions are designed: cement grouts added with 0.65% SNF, 8%, 10%, 13%, and 15% MFA, respectively. As for SEM and MIP samples, only cement grouts with 8% and 13% MFA are investigated.

2 Results and Discussions

2.1 Behavior of the fresh grout

Tab.2 shows the behavior of the grout at fresh stage. From the Ma cone flow time and the bleeding rate in the table we can know the rheological character of the grout. Fresh grout is a multiphase and heterogeneous system mainly composed of cement and water. The grout with high plastic viscosity η_{P_1} normally has low strain rate and correspondingly high flow time. While in the case of very low η_{P_1}, flocculation due to bleeding and severe segregation at

Tab.2 Influence of MFA admixture on the behavior of fresh grout

Type of admixture	Addition rate/%	Ma cone flow time/s			Setting time/h		Bleeding rate/%
		Intial	1 h	2 h	Initial setting	Final setting	
SNF	0.65	21.34	31.21		6.00	6.75	17.65
MFA	8	17.69	17.99	23.34	6.58	7.42	0.30
MFA	10	17.29	17.86	21.22	7.00	7.66	0.12
MFA	13	15.79	18.00	19.32	8.50	9.00	0.00
MFA	15	15.76	17.38	19.56	9.25	9.66	0.00

the bottom mouth of the cone also leads to a high flow time. Therefore, in order to decrease the Ma cone flow time it is necessary to improve the pseudo-plasticity of the grout, i.e. to achieve low η_{P_1} at the shear stress of pumping pressure or self-weight and relatively moderate η_{P_1} at placement. Superplasticizer will effectively lower η_{P_1} and leads to more severe sedimentation of the solid particle and bleeding of the free water. Therefore, grout with SNF shows higher Ma cone flow time and much higher bleeding rate compared with the grout with MFA. The addition of MFA effectively improves the rheological characters of the grout. Not only the Ma cone flow time decreases obviously, but also the bleeding rate tends to be zero. This is due to the special function of pseudo-plasticity of the water-soluble polymer constituent in the admixture. Bleeding water trapped in the grouted duct will collect at high points and form voids or slush, leaving tendon more vulnerable to attack by aggressive agents. Such kinds of grout cannot transfer the force anticipatively but endanger the structure strongly. Moreover, the addition of MFA improves the fluidity retention ability. The Ma cone flow time of the grout with 15% MFA increases by 10.3% after 1 h and 24.1% after 2 h, while that of the grout with 0.65% SNF increases by 46.3% after 1 h and loss fluidity completely after 2 h. High fluidity retention ability is necessary to ensure enough construction time under the condition of hot weather, which is very important for the engineering practice. The addition of 8% to 15% MFA also increases the setting time by about 0.5 to 3 h, and does not change the time from initial to final setting.

2.2 Mechanical performance of the hardened grout

Tab.3 shows the influence of the admixtures on the mechanical performance of the grout. At the same water to cement ratio, the addition of MFA can effectively improve the strength of the grout, especially the steel bar bond strength. Compared with the addition of 0.65% SNF, the addition of 13% MFA increases the flexural strength by 42.6% at 3 d and 12.9% at 28 d, the compressive strength by 26.8% at 3 d and 19.0% at 28 d, and the steel bar bond strength by 313% at the age of 28 d. The bond strength depends on the behavior of the interfacial zone between the steel bar and the grout. Keeping the water to cement ratio constant, it is mostly influenced by the bleeding rate and the shrinkage of the grout. The addition of MFA effectively lowers the bleeding rate and builds up proper expanding compression around the bar and thus increases the bond strength, which effectively ensures the force transfer between the grout and the prestressed tendon. Tab.3 also demonstrates that the strengthening effect of MFA improves when MFA amount increases from 8% to 13% and can be expected better under the restrained condition in the practical engineering. The 28 d compressive strength values are above 55 MPa for all the grouts incorporated with MFA.

Tab.3 Mechanical performance of the grout

Type of admixture	Addition rate/%	Flexural strength/MPa			Compressive Strength/MPa			Steel bar bond strength/MPa
		3 d	7 d	28 d	3 d	7 d	28 d	
SNF	0.65	4.25	5.24	8.56	18.3	22.3	52.5	0.63
MFA	8	4.87	5.6	9.28	24.2	36.5	59.1	2.15
MFA	10	4.95	5.91	9.77	24.0	35.9	59.4	2.41
MFA	13	6.06	6.63	9.66	25.2	37.1	62.5	2.60
MFA	**15**	**6.25**	**6.52**	**9.69**	**21.0**	**39.1**	**64.4**	**3.01**

2.3 Deformation behavior of the grout

The cement based grout material is under nearly closed condition after being injected into the cavity. Due to the density difference between the hydration products and the reactants, the aging of the grout will always be accompanied by chemical shrinkage. This kind of chemical shrinkage is compensated by macro volume reduction before the hardened structure is formed[6,7]. Because the skeleton of the grout is still too weak to provide enough restriction at this time, the volume reduction value may be great enough to affect the grouting compaction degree of the cavity.

Once the solid framework forms, further hydration will be compensated by the creation of new pores in the hardened structure and consume the capillary water. In the closed condition of the concrete core, additional water cannot be transported from outside, self desiccation will be induced in this grout with water to cement ratio 0.37, which will lead to autogenous shrinkage of the hardened grout. Autogenous shrinkage in the hardened stage will cause tensile stress in the grout due to the restrain of the tendon and the surrounding concrete. Once the stress exceeds the tensile stress of the grout, cracks will be induced at the interface and weaken or even lose the function of the grout. The autogenous shrinkage value may be 1 to 2 magnitudes higher than that of mortar or concrete due to no restraint of the aggregate inside the grout system and thus can be a major problem in the post-tensioned prestressed concrete structure.

Fig.2 shows the volume change of the grouts from 0.5 to 24 h after the mixing with water. The volume of the grout added with SNF decreases rapidly within the initial 6 h due to its free chemical shrinkage. After that the grout begins to set. Further chemical shrinkage is restrained by the structure formation and the volume decrease slows down. The total volume reduction percentage is more than 4% at the age of 24 h, which may induce large interspaces and can be filled in with the further hydration of the cement. The addition of MFA admixture effectively decreases the initial volume shrinkage and shows some expansion with up to 10% addition rate. The volume of the grouts with 10% and 13% MFA increases gradually from 0.5 h after mixing with water and reaches the maximum value, which is nearly 1%, at 2 to 5 h. This expansion before setting will not cause high stress in the structure due to large creep relaxation of the fresh grout. After that the volume begins to decrease gradually and still shows a little remnant expansion at the age of 1 d. This remnant expansion can effectively improve the compaction degree of the grout, especially for the flat corrugated pipe, and can build up some pre-compression in the structure to compensate for the part of the latter shrinkage of the grout. Compared with the uncontrollable rapid deflation of ordinary aluminum powder, the expansion speed is effectively under control due to the retarding agent and the surface-treatment of aluminum powder in the MFA. Such expansion can be more easily ensured in the construction site and thus has great important practical significance.

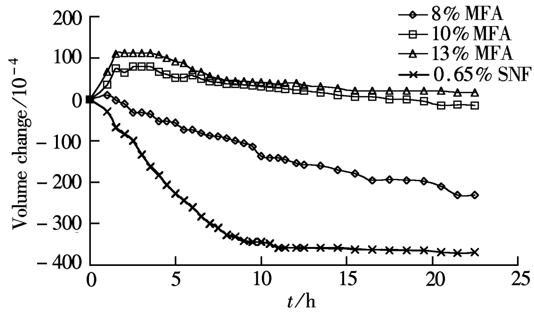

Fig.2 Influence of admixtures on the deformation behavior before 24 h

Fig.3 shows the deformational behavior of the hardened grout with different admixtures in water as well as in sealed condition. The grout to which only superplasticizer is added shows a little expansion in water. The addition of MFA induces large expansion in the hardened grout ($1\ 540 \times 10^{-6}$ at 60 d in water with 13% MFA). The expansion value of the grout in water increases with the MFA addition rate. Such expansion is contributed to the ettringite crystallization in the restricted space and will compensate for the autogenous shrinkage with further hydration of the cement. The free autogenous shrinkage of the grout to which only superplasticizer is added is nearly equal to $1\ 000 \times 10^{-6}$. Such high shrinkage will induce large shrinkage stress under the restraint of the tendon or surrounding concrete and cause cracks in the system. Due to the compensating effect of MFA, the autogenous shrinkage of the grout with 13% MFA at 60 d is lower than 200×10^{-6} and decreases by 335% compared with that of the grout to which only superplasticizer is added.

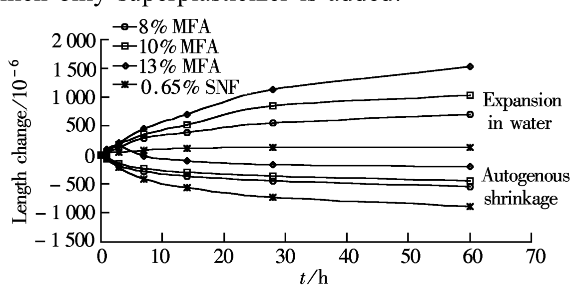

Fig.3 Influence of admixtures on the deformation behavior of the hardened grout

2.4 Microstructure evolution of the MFA grout

Fig.4 shows the pore structure evolution of the grout with 13% MFA (magnified by 50 times) over time. Pores with the size of about 100 μm can be seen in the paste at the age of 3 d (Fig.4(a)). Such pores are the bubbles generated from the reaction of the aluminum powder in MFA with the calcium hydroxide. However, these large pores can be gradually filled with new hydration products with further hydration of the grout (Fig.4(b)). The pore system is obviously improved with hydration age and few large pores can be seen any more in the SEM photograph of the paste with MFA at the age of 43 d (Fig.4(c)). Fig.5 presents the crystal hydration products in the MFA paste at the age of 7 d. It can be seen obviously that ettringite formed in the paste. This needle or fiber shape ettrigite interweaved with the CSH gel and filled in the large pores as well as building expansion pressure in the relatively restricted space of the finer pores.

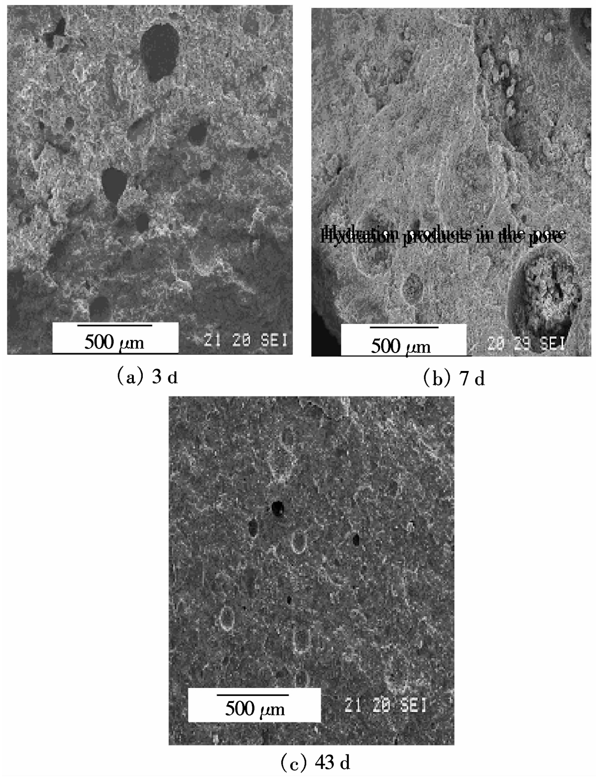

Fig.4 Pore structure evolution of 13% MFA paste with time (SEM)

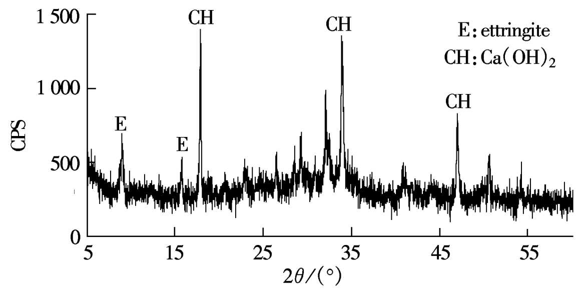

Fig.5 Result of X-rays of 13% MFA paste (7 d)

The results in Tab.4 of the MIP tests show that with the progressing of the cement hydration the total porosity of the grout decreases. The percentage of gel pores (< 10 nm) increases obviously while capillary pores (100 to 1 000 nm) and the large pores (> 1 000 nm) decrease to a large extent. Keeping the cement to water ratio constant, the percentage of the gel pores at 43 d increases by 67.8% when the addition ratio of MFA increases from 8% to 13%. However, the total porosity of the grout changes little with the addition rate, which means that the addition of MFA cannot reduce the total porosity but rather refine the large pores and improve the pore structure of the grout effectively.

Tab.4 Pore structure of paste

Age/d	Addition rate of MFA/%	Pore size distribution/%				Total porosity/%
		< 10 nm	10 − 100 nm	100 − 1 000 nm	> 1 000 nm	
3	8	43.4	38.6	10.8	7.2	43.36
	13	43.5	38.7	10.8	7.0	44.87
7	8	54.9	40.0	1.8	3.3	37.32
	13	54.6	40.9	1.7	2.8	37.27
43	8	54.0	41.4	1.0	3.6	33.22
	13	90.6	4.7	2.8	1.9	30.09

Microstructure test results show that the chemical shrinkage at the fresh stage of the grout is compensated by the internal bubble reacting from the initial expanding constituent in MFA with the hydration product of the grout, which introduces some large pores(about 100 μm) in the hardened structure. However, further hydration products will refine these large pores gradually. The addition of MFA in the grout produces a large quantity of fiber or needle shape ettringite, which is an important expansion source at the later age as well as contributing to the refinement of the large pores. It is the multifunctioning of the constituents in MFA which supported the volume stability through the whole hydration process as well as providing refined pore structure of the grout.

3 Conclusions

With the multifunction of the MFA, high performance grout material can be prepared, which shows excellent rheological properties as well as high volume stability at every stage of the hydration process of the grout.

1) With the multifunction of superplasticizing

and pseudo-plasticity of the constituents in multifunctional admixture, the grout achieved high fluidity with no bleeding and good fluidity retention ability at the fresh stage.

2) The lowered bleeding rate and proper expansion of MFA improve the mechanical performance of the grout, especially increasing the steel bar bond strength by 313% at the age of 28 d.

3) The addition of the MFA effectively decreases the initial volume shrinkage by gradually expanding 0.5 h after mixing with water and reaches the maximum value of about 1% at 2 to 5 h. It then begins to decrease gradually and still shows a little remnant expansion at the age of 1 d, which is easier to ensure in a construction site compared with the rapid deflation using aluminum powder.

4) Due to the compensating shrinkage effect of the grout, the autogenous shrinkage of the grout with 13% MFA at 60 d decreases by 335% compared with that of the grout-only-added mixture with SNF and is lower than 200×10^{-6}, which is in the range of the ultimate tensile strain of cement paste.

5) Microstructure analysis shows that it is the co-action of the initial bubble reaction and latter ettringite crystallization that supports the volume stability through the whole hydration process as well as providing refined pore structure of the grout.

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后张有粘结预应力结构灌浆料性能研究

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摘要: 采用波特兰水泥和一种多功能的外加剂(MFA), 配制出具有高流动性和体积稳定性的高性能灌浆料, 并对其流变性能和力学性能进行了试验研究. MFA 的加入有效地改善了浆体的假塑性, 不仅显著降低了马氏锥的流动时间, 而且消除了浆体的泌水. 对浆体在新拌阶段和硬化阶段的变形行为进行了全过程的试验研究. 采用 MIP, SEM 和 X-rays 等测试手段对浆体微观结构的演变进行了分析. 试验结果表明, 早期的发气以及后期钙矾石结晶的协同作用, 不仅保障了灌浆料在整个水化过程中的体积稳定性, 而且细化了孔结构.

关键词: 后张法; 水泥; 灌浆; 变形行为; 微观结构; 外加剂

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