Experimental Study and Analysis on the Durability of Concrete in Underground Engineering

Z Yang 1*, Y N Huang2, L Zhu2, Y H Liu2, Y Li2 and Z K Hou1

1 Guangzhou Institute of Building Science Co.,Ltd., Guangzhou 510440
2 Guangzhou Testing Center of Construction Quality and Safety Co., Ltd., Guangzhou 510440

* yangzhuo1207@126.com

Abstract: The underground environment is much more complicated than the overground environment. Concrete in underground engineering bears complex environmental effects such as soil stress, water penetration stress, and soil salt erosion. The durability of concrete directly determines the service life of underground engineering. In this paper, considering the soil stress, the chloride ion, sulfate attack and permeability resistance of concrete were tested in the laboratory. The results show that fly ash has excellent resistance to sulfate attack, and when fly ash content is 20% or 30%, the concrete specimens have the best chloride ion penetration resistance and water penetration resistance. Under the effect of preload stress, when the preload stress level is less than 20%, the capacity of concrete stress cannot be reduced greatly, but when the preload stress level is greater than 20%, the concrete durability performance decreases rapidly.

1 Introduction

With the acceleration of urban construction speed and urbanization scale, the development of urban underground space has become an important way of sustainable development of urbanization [1]. However, the underground engineering concrete is filled with soil and groundwater, which have an important effect on the performance of the concrete structure such as impermeability, salt erosion and carbonation resistance [2,3]. At present, in the early underground engineering in China, concrete engineering in the underground humid environment has appeared serious durability problems, and the subsequent repair will consume a lot of manpower and material resources. Developed countries such as the United States, Germany, and Japan spend 12% of the total investment in underground engineering concrete repairs each year [4-6].

The durability of concrete structures is always related to the exposed environment [7]. The environment of the underground structure is much more complicated than the overground environment. The environment of the underground concrete includes the erosive substances in the soil and groundwater, groundwater seepage and soil pressure stress. The more serious is that some concrete is in the environment of alternating dry and wet groundwater, which has more serious damage to the durability of concrete [8-10]. Xiao et al. [11] studied the effect of aggregate gradation and nano-SiO2 on the permeability resistance of concrete, and found that when the Fuller index of aggregate is between 0.4-1.0, the microstructure of concrete is the densest and the strongest permeability resistance, and nano-SiO2 reduces the internal connectivity of concrete, greatly enhancing the impermeability of concrete. Lin et al. [12] applied the HYDROGEOCHE chemical reaction transport model, which mainly caused...
of underground concrete degradation include H⁺, SO₄²⁻ and Cl⁻ in groundwater. Jahandari et al. [13] studied the effect of groundwater on the compressive strength of lime concrete. It can be clearly found that water has a significant effect on the reduction of lime concrete strength. Under 100% groundwater immersion environment, the compressive strength of specimen 60d decreases 42%. Garcia et al. [14] prepared low-pH concrete with a large amount of silica fume and fly ash, which has good resistance to long-term groundwater erosion.

At present, the existing research on the durability of concrete in underground engineering mainly at the level of concrete materials, and there are few studies on the soil squeezing stress, the dry-wet cycles of groundwater, and electrochemical penetration. In this paper, the factors affecting the durability of concrete in underground engineering are given, and considering soil stress, the resistance of concrete to chloride ion, sulfate attack and permeability is tested in the laboratory.

2 Influence factors of concrete durability in underground engineering

The influencing factors of the durability of concrete in underground engineering, including environmental factors, design factors and construction factors. The design factors mainly include the design shape of concrete structure, the protective layer thickness and the concrete strength, while the construction factors mainly include the construction method and construction process. Compared with environmental factors, design factors and construction factors have less effect on the durability of underground concrete. The environmental complexity of underground engineering is an important factor causing the durability of concrete, including the erosion and infiltration of groundwater. Under the action of groundwater pressure, free water constantly passes through concrete, leading to the cracking and destruction of concrete structures. The biodegradation and erosion of the concrete material, the soil is rich in minerals and microorganisms, and the microorganisms multiply on the surface of the concrete, which will lead to the corrosion and deterioration of the concrete. In the complex stress environment, such as soil pressure and seepage pressure, concrete will experience compression or tensile stress, and the acceleration of stress will appear with the aggravation of durability damage. Under the effect of stray current, large transport cables or power supply are mostly underground, and there are many stray microcurrents underground. In this environment, Cl⁻ or SO₄²⁻ ions in moist soil will accelerate the erosion of concrete and form an electrochemical erosion environment.

3 Test materials and test methods

3.1 Test raw materials and specimen preparation

The cementation materials selected include P.O 42.5 Portland cement and Class F fly ash. The main chemical composition of cement and fly ash tested by X-ray fluorescence spectrometry (XRF) are shown in Table 1. Fine aggregate is used standard sand with a fineness modulus of 2.7, and coarse aggregate is used 5mm-20mm continuous graded ordinary gravel. The chemical reagents were Sinopharm sodium chloride chemical pure (NaCl, 99.5%) and sodium sulfate chemical pure (Na₂SO₄, 99.5%). Based on the compressive stress of concrete in underground engineering, the pre-loading stress levels of 0%, 10%, 20%, 30% and 40% were selected in this paper to test the durability of each specimen subjected to the stress level. The fly ash content is 0%, 10%, 20%, 30%, 40% and 50% respectively. The water-binder ratio of concrete is 0.32, and the water-reducing agent content is 0.6%. The specific mix proportion is shown in Table 2. Concrete with fly ash content of 20% was used to test its durability under different preloaded stress levels.

Use the forced concrete mixer to mix the cementitious material and coarse and fine aggregate evenly, then mix the water-reducing agent and water evenly, then pour into the mixer, continue to stir for 5 minutes. Quickly pour the new paste into a 100mm×100mm×100mm cube mold, 100mm×200mm cylinder mold and cone mold (internal diameter of the upper mouth is 175mm, internal diameter of the lower mouth is 185mm, and height is 150mm). The shaking table vibrates 60s, and after covering with a thin polyethylene film and demolded after 1 d of curing at standard curing room (RH= 95±1% and T= 20±2 °C), the mold is removed and then moved to the standard curing room for curing until the test age.
Table 1. The main chemical composition of cement and fly ash/%

| Materials | SiO₂ | Al₂O₃ | CaO | Fe₂O₃ | SO₃ | MgO | Na₂O | LOI |
|-----------|------|-------|-----|-------|-----|-----|------|-----|
| Cement    | 20.09| 6.15  | 62.13| 2.78  | 3.27| 1.10| 0.12 | 4.36|
| Fly ash   | 29.79| 52.03 | 7.10| 1.96  | 0.07| 0.21| -0.46| 8.38|

Table 2. Mix proportion of concrete kg/m³

|       | Cement | Fly ash | Fine aggregates | Coarse aggregates | Water |
|-------|--------|---------|-----------------|-------------------|-------|
| FA-0  | 565    | 0       | 525             | 1017              | 180.8 |
| FA-10 | 508.5  | 56.5    | 525             | 1017              | 180.8 |
| FA-20 | 452    | 113     | 525             | 1017              | 180.8 |
| FA-30 | 395.5  | 169.5   | 525             | 1017              | 180.8 |
| FA-40 | 339    | 226     | 525             | 1017              | 180.8 |
| FA-50 | 282.5  | 282.5   | 525             | 1017              | 180.8 |

3.2 Test method
In this paper, the compressive strength and durability of the concrete samples were tested, and the durability was all carried out according to GB/T50082-2009.

(1) Compressive strength: Specimens of 100mm×100mm×100mm were used for the compressive strength test, and the YAM-500 press was used for the test, and the loading speed is 0.5MPa/s. The compressive strength of 3d, 28d and 90d were tested respectively, and the compressive strength is the average value of three test blocks.

(2) Chloride diffusion coefficient: Cut the ∅100mm×200mm cylinder block into three ∅100mm×50mm small cylinders and test the chloride diffusion coefficient of the concrete using the RCM method.

(3) Sulfate attack: Cube test blocks of 100mm×100mm×100mm were used for the test, and the specimens were immersed in 5% sulfate solution for 90d, with the compressive strength corrosion resistance coefficient K as the measurement standard:

\[ K = \frac{f_{c0}}{f_{cn}} \times 100\% \] (1)

Where: F_{cn} and F_{c0} respectively represent the compressive strength values of sulfate attack specimens and standard curing specimens at the same age, accurate to 0.1MPa.

(4) Water penetration resistance: The average water seepage height under the action of constant water pressure represents the water permeability resistance of concrete. The 28d cone specimens were sealed with paraffin, and the test block was screwed and pressed into the test mold, and the water pressure was constantly controlled at 1.2MPa within 24 hours. After the test is completed, Split the test blocks, and 10 measuring points are measured at regular intervals along with the water-mark with a steel ruler, accurate to 1 mm, the seepage water height of concrete is taken from the average of ten measuring points. The test is stopped when water seeps on the upper surface of the specimens during the test.

4 Results and discussion

4.1 Compressive strength test results
Compressive strength is the most intuitive indicator of concrete application. Figure 1 shows the compressive strength of concrete with different fly ash content. The 3d compressive strength decreases with the increase of fly ash content, and compared with FA-0 specimen, the compressive strength of concrete with 10%, 20%, 30%, 40% and 50% fly ash content decreases by 3.75%, 10.85%, 13.11%, 12.83% and 17.60%, respectively. At 28 days, the addition 10% fly ash of concrete shows the highest compressive strength. Compared with FA-0 specimen, the compressive strength of concrete with 10%, 20%, 30%, 40% and 50% fly ash content decreases by -1.53%, 1.87%, 7.92%, 9.71% and 14.02% respectively. When fly ash content exceeds 20%, the compressive strength decreases greatly. At 90 days, compared with FA-0 specimen, the compressive strength of concrete with 10%, 20%, 30%, 40% and 50% fly ash decreases by -5.54%, -3.64%, 0.12%, 1.87% and 3.81%, respectively. The compressive
strength of concrete with 10% and 20% fly ash content is higher than that of FA-0 specimen, mainly due to the secondary hydration reaction of fly ash makes the internal structure of concrete denser. Comparing the compressive strength of 3d, 28d and 90d, it can be found that a large amount of fly ash has little effect on the compressive strength in the later period, which means that the fly ash only plays a filling role in the early stage of concrete strength development.

4.2 Chloride penetration resistance test results

Figure 2 shows the chloride ion diffusion coefficient of concrete. Figure 2(a) is the fly ash content factor, it can be clearly found that with the increase of fly ash content, the chloride ion diffusion coefficient of concrete shows a decrease first and then an increase. When the fly ash content is 30%, the chloride diffusion coefficient of concrete is the lowest, which is $3.17 \times 10^{-12} \text{m}^2/\text{s}$. Figure 2(b) is the preload stress level factor, compared with the FA-20 specimen, when the pre-load stress level is 10%, 20%, 30% and 40%, the chloride diffusion coefficient of concrete increases by 1.07%, 7.08%, 63.73% and 408.37%, respectively. When the preload stress level exceeds 20%, the chloride diffusion coefficient of concrete begins to increase rapidly. This is mainly because at the 28d age, when the fly ash content is too high, the production of Ca(OH)$_2$ decreases, which reduces the alkalinity value inside the concrete. However, fly ash does not fully react at the 28d age, and the reduction of compressive strength also directly affects the chloride ion diffusion resistance of concrete.
4.3 Sulfate attack resistance test results

Figure 3 shows the compressive strength corrosion resistance coefficient of concrete. Figure 3(a) is the fly ash content factor, it can be clearly found that with the increase of fly ash content, the compressive strength corrosion resistance coefficient of concrete increases. Compared with FA-0 specimen, the compressive strength corrosion resistance coefficient of concrete with 10%, 20%, 30%, 40% and 50% fly ash increase by 2.0%, 4.64%, 9.39%, 10.13% and 13.82%, respectively, it can be clearly found that the addition of fly ash contributes to the sulfate attack resistance of concrete. Figure 3(b) is the preload stress level factor, it is obvious that with the increase of preload stress level, the compressive strength corrosion resistance coefficient of concrete decreases greatly. When the preload stress level is 10%, 20%, 30% and 40%, the compressive strength corrosion resistance coefficient of concrete decreases 8.6%, 12.5%, 28.6% and 48.1%, respectively.

Sulfate attack is mainly due to the reaction of SO$_4^{2-}$ with the cement hydration product Ca(OH)$_2$ and tricalcium aluminate to form calcium vanadite, which is in the form of a thin bar or a spicular. In the curing process, the solid phase volume of ettringite can increase by 90% as it expands with water absorption. If the amount of ettringite produced is small, it will play a role in improving the compactness and strength of concrete inside the concrete; however, if a large amount of ettringite is columnar after absorbing water, a large internal stress is generated inside the concrete, resulting in the deterioration and expansion of the concrete. The addition of fly ash reduces the formation of Ca(OH)$_2$. As the hydration reaction progresses, a part of Ca(OH)$_2$ will participate in the secondary hydration reaction of fly ash, further reducing the formation of ettringite in concrete. Therefore, with the increase of fly ash content, the amount of ettringite in the concrete decreases and fills the pores in the concrete. Furthermore, in the SO$_4^{2-}$ environment, the fly ash is activated by the sulfate and the reaction is more sufficient, resulting in the compressive strength increases.

![Graph showing compressive strength corrosion resistance coefficient of concrete](image1)

4.4 Permeability resistance test results

Figure 4 shows the water penetration depth of concrete, Figure 4(a) is the fly ash content factor, and it can be clearly seen that with the increase of fly ash content, the water permeability resistance shows a trend of first increasing and then decreasing. When the fly ash content is 0%, 10%, 20%, 30%, 40% and 50%, the water penetration depth is 47.2mm, 43.4mm, 41.6mm, 41.7mm, 49.8mm and 50.6mm, respectively. Fly ash content of 20% and 30% shows excellent water penetration resistance, mainly due to the addition of a small amount of fly ash provides active SiO$_2$ and Al$_2$O$_3$ for cement hydration reaction. Furthermore, fly ash can also play a role in filling pores, enhancing the compactness of the concrete structure. Figure 4(b) is the preload stress level factor, when the preload stress level is 40%, the water penetration depth exceeds 150mm when the test reaches 16h, and the test is terminated early. Compared with FA-20 specimen, the water penetration depth of concrete increased by 28.37%, 36.30%, 150.0% and 260.58% when the preload stress level were 10%, 20%, 30% and 40%, respectively. When the
preload stress level exceeds 20%, the depth of water permeability increases rapidly. In underground engineering, when the concrete is subjected to large soil stress, it is not conducive to its water penetration resistance.

![Graph showing the relationship between depth of water penetration and fly ash content](image1)

![Graph showing the relationship between depth of water penetration and preload stress level](image2)

**Figure 4.** Depth of water penetration of concrete

5 Conclusions

(1) The addition of fly ash is not conducive to the increase of early compressive strength of concrete. The concrete specimen with 10% fly ash has the highest compressive strength at 28d; the concrete test with 20% fly ash has the highest compressive strength at 90d.

(2) The fly ash mixed into the concrete mainly played a filling role in the early stage. With the progress of the secondary hydration reaction, the long-term sulfate attack resistance increased. When fly ash content is 30%, the chloride diffusion coefficient of concrete is the lowest, and when fly ash content is 20% or 30%, concrete shows excellent water permeability resistance.

(3) Underground engineering concrete has long-term effects of soil stress and water penetration stress. When the preload stress level is not large (within 20%), the chloride ion diffusion coefficient, compressive strength corrosion resistance coefficient and water penetration depth of concrete do not increase greatly. Overall, when the preload stress is large, it is not conducive to the durability of concrete. In the design of underground engineering, the stress level of the soil is an important factor that affects the durability of concrete.

Acknowledgments

The authors acknowledge the financial support from Guangzhou Science and Technology Plan Project (201906010044) and Guangdong Basic and Applied Basic Research Foundation (2019A1515110836).

References

[1] Wang JM, Qin Q, Hu SJ and Wu KN 2016 A concrete material with waste coal gangue and fly ash used for farmland drainage in high groundwater level areas. J. Clean. Prod. 112, 631-8.

[2] Gonzalez-santamaria DE, Angulo M, Ruiz AI, Fernandez R, Ortega A and Cuevas J 2018 Low-PH cement-bentonite perturbations in a small-scale pilot laboratory experiment. Clay Miner. 53(2), 237-54.

[3] Leemann A and Loser R 2011 Analysis of concrete in a vertical ventilation shaft exposed to sulfate-containing groundwater for 45 years. Cem. Concr. Compos. 33(1), 74-83.

[4] Regmi G, Indraratna B, Nghiem LD and Banasiak L 2011 Evaluating waste concrete for the treatment of acid sulphate soil groundwater from coastal floodplains. Desalin. Water Treat. 32(1-3), 126-32.
[5] Elliotis MC 2019 A mathematical model for a steady-state seepage flow of groundwater under a reinforced concrete dam. Appl. Comput. Geosci. 1, 100003.

[6] Li B, Fang HY, Yang KJ, Tan PL and Wang FM 2019 Dynamic analysis of concrete pipes under the coupled effects of traffic load and groundwater level fluctuations. Energy Sci. Eng. 8(1), 203-15.

[7] Isabel G, Andre B, Wolfgang K, Martin D and Florian M 2019 Durability of shotcrete for underground support-review and update. Constr. Build. Mater. 202, 465-93.

[8] Vigantas AZ, Svajunas J and Giedrius Z 2009 Hydrotechnical concrete with local aggregates and them using for monolithic structures. Eng. Struc. Technol. 1(2), 102-10.

[9] Jiang LH, Xue X, Zhang WD, Yang JN, Zhang HQ, Li YW, Zhang RP, Zhang ZY, Xu LJ, Qu J, Song JR and Qin J 2015 The investigation of factors affecting the water impermeability of inorganic sodium silicate-based concrete sealers. Constr. Build. Mater. 93, 729-36.

[10] Zhang BL, Tan HB, Shen WG, Xu GL, Ma BG and Ji XL 2018 Nano-silica and silica fume modified cement mortar used as surface protection material to enhance the impermeability. Cem. Concr. Compos. 92, 7-17.

[11] Xiao HG, Liu R, Zhang FL, Liu M and Li H 2018 Role of nano-SiO2 in improving the microstructure and impermeability of concrete with different aggregate gradations. Constr. Build Mater. 188, 537-45.

[12] Lin WS, Liu CW and Li MH 2016 Influences of specific ions in groundwater on concrete degradation in subsurface engineered barrier system. SpringerPlus 5(1), 1-18.

[13] Jahandari S, Toufigh MM, Li J and Saberian M 2017 Laboratory study of the effect of degrees of saturation on lime concrete resistance due to the groundwater level increment. Geotechn. Geolod. Eng. 36(1), 413-24.

[14] Garcia Calvo JL, Hidalgo A, Alonso C and Fernandez Luco L 2010 Development of low-PH cementitious materials for HLRW repositories: resistance against ground waters aggression. Cem. Concr. Res. 40(8), 1290-97.