Durability And Life Prediction of Fly Ash Geopolymer Concrete In Corrosion Environments Caused By Dry And Wet Circulation

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Research Article

Keywords: Geopolymer concrete , Life prediction , Expansion internal force

Posted Date: September 7th, 2021

DOI: <https://doi.org/10.21203/rs.3.rs-705730/v1>

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Version of Record: A version of this preprint was published at Environmental Science and Pollution Research on February 2nd, 2022. See the published version at <https://doi.org/10.1007/s11356-022-18954-0>.

Abstract

The use of tailings, waste rock, fly ash and slag to prepare geopolymer concrete can effectively solve the problems of land resources occupied by tailings and waste rock, low utilization rate and environmental pollution. Using a dry-wet circulation method, fly ash for a different corrosion solution to geopolymer concrete (referred to as TWGPC) was analysed. Through an appearance change, the corrosion resistance coefficient of the compressive strength, relative dynamic elastic modulus, tensile splitting strength, relative mass and durability were investigated, using scanning electron microscopy (SEM) analysis of the microstructure, The life of TWGPC was predicted based on the GM(1,1) prediction model of grey system theory. The test results show that with an increase in the number of dry-wet cycles, the surface of the specimen crystallizes, cracks, spalls and exhibits other phenomena. The compressive strength corrosion coefficient, relative dynamic elastic modulus, crack tensile strength and relative mass show a trend of increasing first and then decreasing, finally reaching the peak value after 40 cycles. The erosion products generated by the early reaction fill the slurry aggregate pores and improve the strength of TWGPC. In a later stage, a large number of erosion products absorb water and expand, the internal pores of TWGPC are connected, leading to a decrease in strength. Cl^- inhibits the corrosion of SO_4^{2-} in concrete and improves the durability of concrete.

Introduction

The world produces nearly 14 billion tonnes of solid waste such as tailings and waste rock every year (Khaldoun et al. 2016). These solid wastes contain sulfide metals and metal-like minerals and mainly accumulate on surfaces (Adiansyah et al. 2015; Liu et al. 2020), which not only occupies a large amount of storage space but also pollutes surface water and causes potential safety hazards to the ecological environment (Candeias et al. 2015; Chen et al. 2018). According to statistics, the total reserves of waste rock and tailings and other solid wastes in China have exceeded 60 billion tonnes. In 2015, the annual output of tailings, fly ash (FA) and slag was 950 million tonnes, 440 million tonnes and 310 million tonnes, respectively, and the utilization rates were 28.5%, 86.4% and 88.2%, respectively (Liu et al. 2018). To effectively solve the problems of a low utilization rate of solid waste and large environmental pollution (Zhao et al. 2020), FA can be used to partially replace cement, tailings and waste rock can be used to replace natural sand, and breakstone can be utilized to prepare concrete (Dandautiya and Singh 2019).

In recent years, many scholars have carried out considerable research on the performance of geopolymer concrete composed of waste rock and tailings instead of aggregates and slag and FA instead of cementitious materials (Parathi et al. 2021). Li et al. (2018) studied the carbonation resistance of geopolymer concrete, carried out accelerated carbonation tests on FA and ground blast furnace slag (BFS) with different dosages and ratios, and found that the carbonation resistance decreased. With regard to the FA dosage and water /FA ratio, using a retarder and thermal curing helped improve the carbonation resistance of geopolymer concrete. Peng et al. (2018) studied the effects of the FA and BFS content and substitution rate on the compressive strength and permeability of concrete and found that at the same substitution rate, FA had a greater effect on the compressive strength of concrete than BFS, and

both FA and BFS could effectively reduce the permeability of concrete. Nguyen et al. (2019) studied the effects of replacing natural sand with nickel-and-iron slag (FNS) sand and replacing ordinary Portland cement with FA on the carbonation resistance and interface transition zone (ITZ) of concrete. By using scanning electron microscopy (SEM) and energy dispersive spectroscopy (EDS) to analyse the microstructure of the ITZ, it was found that the carbonation resistance of concrete could be improved when the substitution rate of FNS sand was 50%. Tang et al. (2019) studied the effects of the FA substitution rate containing recycled aggregate and the mixing amount of grind-blast furnace slag (GGBFS) on the uniaxial compression performance of concrete and found that increasing the mixing amount of slag can reduce the peak stress of the recycled aggregate. Guo et al. (2020) adopted recycled concrete aggregate (RCA) to replace natural aggregate. The supplementary cementing material (SCM) composed of slag and silica fume replaced cement, and the influence of different mixes on the mechanical properties and durability of self-compacting concrete (SCC) was analysed. It was found that RCA could improve the performance of SCC by compensating for the lack of SCM. Huang et al. (2018) studied waste stone powder by using the method of single mixing and compound mixing. The influence of FA and slag powder on the durability of concrete at different doses was as follows. When a single dose was less than 20%, the concrete had good frost resistance and sulfate resistance, and when the total dose was less than 30%, the concrete had good durability. Balraj et al. (2020) used rice husk ash (RHA) as a partial substitute for cement to study the water absorption performance of concrete of different types and sizes and established an empirical model for the water absorption performance. These researchs found that compared with ordinary concrete, when the replacement rate of RHA was 20%, the water absorption capacity of concrete decreased to 1/3 of the original, and this model could accurately predict the water absorption capacity of concrete. Xu et al. (2017) studied the influence of slag powder and FA content on the early hydration process of concrete under different curing temperatures and found that the addition of FA promoted early hydration of concrete and enhanced the sensitivity of temperature to its hydration process.

Many scholars have studied the durability of concrete under the action of dry-wet cycles and salt solution erosion. Boopaphi et al. (2021) carried out a study on FA concrete before and after seawater erosion, both uncoated and coated with epoxy resin and acrylic resin. Through mechanical tests and microstructure analysis, they found that the coating of epoxy resin and acrylic resin facilitated the good bonding performance and durability of concrete. Chen et al. (2016) studied the erosive effects of chloride salt and sulfate composite solutions on ordinary Portland cement (OPC) samples of FA slag under the action of a dry-wet cycle and found that a high-concentration composite solution could reduce OPC damage caused by this process. He et al. (2020) studied concrete deterioration under the combined action of wetting and drying cycles and sulfate and found that the concrete porosity increased with increasing cycles, accelerating the process of concrete cracking and deterioration. Vishwakarma et al. (2020) conducted a study on modified concrete mixed with FA and nanomaterials under the action of sulfate erosion and found that partial substitution of FA for cement and a reduction of the C_3A content could both improve the sulfate erosion resistance of concrete. Özcan and Karakoç (2019) analysed the mechanical properties and microstructure of geopolymer concrete under the action of sulfate and chloride solutions. By

measuring its compressive strength and mass, it was found that the sulfate solution had a more obvious erosion effect on concrete, and the strength loss rate of samples in the erosion solution decreased with increasing electric field stimulation ratio. Harilal et al. (2021) carried out a study on concrete deterioration under the action of natural seawater, sulfuric acid and magnesium sulfate solution and used a mixture composed of FA, nanoparticles and sodium nitrite inhibitor (CFNI) to partially replace cement. By analysing the concrete mass loss rate and compressive strength, it was found that CFNI showed good corrosion resistance in three corrosion solutions. Yuan et al. (2016) studied the failure process of the specimen under the coupling of dry and wet circulation and sulfate erosion, analysed the correlation with grey association theory, and found that the higher the salt solution concentration was, the worse the internal structure damage.

Previous studies have mainly analysed geopolymer concrete composed of tailings, waste rock, FA and slag in terms of the mixing amount, ratio and substitution rate as well as analysed concrete durability under dry-wet cycles and salt solutions. These studies have provided a theoretical basis for the use of solid waste and have promoted the development of geopolymer concrete and concrete durability in corrosive environments. However, there have been few reports on the durability of geopolymer concrete under wet and dry cycling and corrosive environments. Based on this, the dry-wet circulation method was used for testing. Natural sand was replaced with gravel backfilling materials and waste rock. Slag was used as the admixture, and FA was used as the cementing material. The optimal mixture ratio was determined at different TWGPC corrosion rates, and a durability analysis was conducted. Based on the GM(1,1) life prediction model, the service life of TWGPC under the action of erosion was predicted. The predicted results were compared with the appearance changes, macroscopic mechanical tests and microstructure analysis results, and the feasibility of the model was verified.

Materials And Methods

2.1 Materials

For testing, FA was taken from the Fuxin Power Plant, Liaoning Province, and the grain size was mainly within 300 μm . The particle size of the tailings was less than 2500 μm . Using slag as the admixture, advanced slag powder was produced by Shandong Kangjing Material Co., Ltd., and the density is 2.88 g/cm^3 . Natural sand was used as a fine aggregate, and the grain size was within 4.75 mm. The fineness modulus was determined by screening the natural sand. The screening results are shown in Table 1.

Table 1
Screening test of natural sand

Mesh size	4.75 mm	2.36 mm	1.18 mm	600 μ m	300 μ m	150 μ m	Screening bottom	Total
Triage quality (g)	14.2	117.2	122.2	100	62.4	44.3	39.7	500
Percentage remaining on the screen (%)	2.84	23.44	24.44	20	12.48	8.86	7.94	100
Cumulative sieve residual percentage(%)	2.84	26.28	50.72	70.72	83.2	92.06	100	—

The calculated modulus of natural sand fineness is 3.18. The waste rock is used as coarse aggregate, which was taken from the Baoshan rock dump site in Anshan city, Liaoning Province. Waste rock and gravel exhibited a 5–20 mm continuous gradation. The optimal fit of FA geopolymer concrete is shown in Table 2.

Table 2
Optimal mix ratio of TWGPC

Fly ash	Slag	Tailings	Natural sand	Waste rock	Breakstone	Water-solids ratio
239	159	576.8	144.2	888.8	222.2	0.36

2.2 Test scheme

After preparation, the specimens were put into a curing box (temperature $20 \pm 2^\circ\text{C}$, relative humidity 95%) for standard curing. After 24 hours, the specimens were removed from the mould and cured for 3 d, 7 d and 28 d. After curing the concrete specimen to the set age, it was put into the corresponding salt solution to carry out the dry-wet cycle test. The corrosion solutions were divided into 7 groups according to their types and were named, as shown in Table 3.

Table 3
Types and groups of corrosion solutions

Variety	Clear water	5%Na ₂ SO ₄	10%Na ₂ SO ₄	5%NaCl	10%NaCl	5%Na ₂ SO ₄ + 5%NaCl	10%Na ₂ SO ₄ + 10%NaCl
Group	N	S5	S10	C5	C10	CS5	CS10

During dry and wet cycle testing, the specimens were immersed in a salt solution for 10 hours, basked in natural air for 2 hours, dried for 10 hours, and cooled for 2 hours. The wet-dry cycle was carried out for a total of 24 hours. The cycle process can be implemented as follows: Set the drying temperature to ($80 \pm 5^\circ\text{C}$), replace the solution once every 30 d, ensure that the concentration of the solution is in a certain PH range, and add erosion solutions on a regular basis, making sure that the solution is not more than 20

mm above the upper surface of the specimen. Cycle the dry and wet conditions in the corresponding salt solution 20, 40, 60 and 80 times.

2.3 Test method

The test standard is the standard of the ordinary concrete mechanical performance test method (GB/T50081-2002) (China Academy of Building Research 2002), and a TAW-2000 test machine was used to test the uniaxial compressive strength. The tensile strength test of non-standard concrete was performed on specimens with sizes of 100 mm × 100 mm × 100 mm. The test result was multiplied by a conversion coefficient of 0.85 (China Academy of Building Research 2002). The TWGPC test piece dynamic elastic modulus was 100 mm × 100 mm × 400 mm. Microstructural analysis of the specimen was conducted using SEM. The surface of the specimen after dry and wet cycling was tested for quality.

Results And Discussion

3.1 Appearance change

Figure 1 and Fig. 2 show the appearance changes of TWGPC in different corrosion solutions after 40 and 80 cycles of wetting and drying.

As shown in Fig. 1, under the action of 40 drying-wetting cycles, only a few very small pores existed in group N, a small amount of sulfate and chloride crystals precipitated in group S5 and group C10, a small amount of sulfate and chloride crystals precipitated in Group CS5, partial surface peeling occurred in group S10, and corner peeling in group CS10. As shown in Fig. 2, under the action of 80 drying-wetting cycles, small cracks appeared in group N, a large amount of epidermal peeling appeared in group S5, and the corrosion was more serious in group S10, with a large amount of epidermal peeling and aggregate exposure. Many small cracks appeared in group CS5, and a large number of crystals precipitated out in group CS10, accompanied by partial epidermal peeling.

Compared with Fig. 1 and Fig. 2, with an increase in drying and wetting cycles, the surface cracking and peeling phenomena of TWGPC in 7 corrosion solutions increased (Su and Zhang 2014). In the same solution, the higher the concentration was, the more serious the erosion damage.

3.2 Compressive strength and corrosion resistance coefficient

As shown in Fig. 3, the TWGPC compressive strength corrosion resistance coefficient $K_f(\%)$ changes in different corrosion solutions under the action of a different number of drying and wetting cycles.

As shown in Fig. 3, with an increase in the number of wetting and drying cycles, the corrosion resistance coefficient of TWGPC first increases and then decreases (Liu et al. 2019). Under the action of 40 wetting and drying cycles, the corrosion resistance coefficient of TWGPC reaches its maximum value. The increasing and decreasing trend of the corrosion resistance coefficient of the compressive strength of

specimens in group S10 is more obvious than that in group S5 and group N. The maximum value is 1.45 times the initial value, and the minimum value is only 0.51 times the initial value. The change in the compressive strength corrosion resistance coefficient of the specimens in group C was less than that in group S with the same concentration. The compressive strength corrosion resistance coefficients of the specimens in group C were the lowest after 80 dry and wet cycles, which were 98% and 95%, respectively. At the initial stage when the corrosive solution invades the concrete, the resulting material fills part of the pores in TWGPC to improve the compressive strength of concrete. With increasing drying and wetting cycle time, a large amount of gypsum, ettringite and other products in TWGPC absorb water and expand, resulting in expansion stress (Zhang et al. 2018), the pores in specimens are connected and ruptures occur (Liu et al. 2020).

3.3 Relative dynamic modulus of elasticity

Figure 4 shows the change in the relative dynamic modulus $E_{rd}(\%)$ of the specimen, where E_{rd} is the ratio of the relative modulus of dry and wet cycles n times to that of dry and wet cycles 0 times.

As shown in Fig. 4, the higher the concentration of the same corrosion solution is, the more dry-wetting cycles there are, and the faster the relative dynamic elastic modulus value changes, showing a trend of first increasing and then decreasing. A comparison of group N, group S5 and group S10 was carried out, and the results indicate that the relative value of the dynamic elastic modulus in group N demonstrates the smallest change, followed by group S5, and the largest change is in group S10 with the highest concentration. Compared with the initial value (0 cycle times), when the number of wetting and drying cycles were 40, the dynamic modulus of the S10 and S5 specimens increased by 56.99% and 52.47%, respectively. It was found that the higher the concentration was, the faster the relative value of the dynamic modulus rose. The rise was due to the internal reaction of SO_4^{2-} invasion, resulting in a denser TWGPC structure. Under the action of 40–60 dry-wet cycles, the relative value of the dynamic elastic modulus decreases rapidly, and then the decline rate slows down and tends to be gentle. With more drying and wetting cycles, more SO_4^{2-} invades TWGPC, leading to a rapid chemical reaction. The resulting product absorbs water and generates a swelling force, which destroys the internal structure of TWGPC, leading to an increase in the relative value of the decline rate of the dynamic elastic modulus (Cao et al. 2020).

3.4 Splitting tensile strength

Figure 5 shows the variation in the splitting tensile strength of specimen f_{ts} .

Figure 5 shows that the variation rule of the splitting tensile strength of TWGPC is consistent with the variation rule of the relative dynamic elastic modulus. After 40 wetting and drying cycles, the splitting tensile strength of S10 group changed the most, which increased by 64.22% compared with the initial value, CS10 by 44.41%, and CS5 group by 37.70%. Because Cl^- and SO_4^{2-} enter the TWGPC through the pores, crystals such as Friedel salt, ettringite and gypsum are generated by the reaction, which increases the density of pores and enhances the splitting tensile strength of the specimens. After 80 cycles of

drying and wetting, the splitting tensile strength of the CS10 group decreased by 10.14% and that of the CS5 group decreased by 8.63% relative to the initial value. Due to the large amount of formation of Friedel salt, ettringite and gypsum, the swelling stress in the specimens increased, and the splitting tensile strength decreased.

3.5 Relative quality

Figure 6 shows the relative quality K_m (%) changes in the specimen, and K_m is the ratio of the relative mass of n dry-wet cycles to that of 0 dry-wet cycles.

As shown in Fig. 6, the change in group CS is smaller than that of group S at the same concentration and larger than that of group C at the same concentration, mainly because Cl^- can inhibit the erosion effect of SO_4^{2-} on concrete to some extent (Yin et al. 2019; Sotiriadis et al. 2012), and the higher the Cl^- concentration is, the more obvious the inhibition effect (Yin et al. 2019). Under the action of 40 dry-wetting cycles, the relative mass value of the S10 group was the largest (102.88%) and that of the N group was the smallest (100.60%). After 80 cycles of drying and wetting, the relative mass value of the S10 group was the smallest, which was only 96.19% of the initial value. Crystalline materials are produced to fill the pores, and the quality of TWGPC is increased. As the number of dry-wetting cycles increases, the pores of the specimen increase. During the drying process, a large amount of water and internal crystals are precipitated out through the pores, resulting in a decline in quality. The higher the concentration, the higher the penetration rate of the solution, and the greater the quality declines.

3.6 Microstructure analysis

As shown in Fig. 7 and Fig. 8, SEM (5000×) was employed to characterize the microscopic morphology after 40 and 80 dry and wet cycles.

As shown in the image in Fig. 7(a), large amounts of white flocculent calcium hydrosilicate gel (C-S-H) and calcium silicate aluminate gel (C-A-S-H) exist, and the flocculent reacts with water inside the specimen to fill the pores, making the TWGPC structure denser. As shown in Fig. 8 (a), the internal porosity increases and the number of macropores increases (Liu et al. 2020), and the flocculents between the aggregates absorb water and expand, and are loosely distributed in all parts of the specimen, leading to a decrease in strength.

As shown in Fig. 7(b), a large number of flocculents were observed to contain reaction products such as ettringite to fill the pores. As shown in Fig. 8(b), a large number of fibrous cluster flocculent ettringite and gypsum products are found to gather together with the gel (Wu et al. 2020). SO_4^{2-} intrudes into TWGPC and reacts with C-A-S-H in TWGPC to generate ettringite crystals that absorb water and expand, causing cracks and other damage to the specimen (Yang et al. 2018).

As shown in Fig. 7(c), calcium chloroaluminate exists in various forms, encapsulates the tailings and entangles with the products of cementifying materials to fill the pores and enhance the strength of TWGPC. As shown in Fig. 8(c), large pores appear in the internal structure, and a large number of Friedel

salt crystals are generated in the pores. When Cl^- first intrudes into the interior, there is a bonding effect between the slurry and aggregate. As the number of dry-wet cycles increases, the bonding between the slurry and aggregate decreases, and the strength decreases (Wang et al. 2020; Yao et al. 2019).

As shown in Fig. 7(d), a large number of Friedel crystals and flocculent reaction products exist in the structure, and a small number of bars exist in the gap between the slurry and aggregate. Some products of blocks and flocculents are attached to each other, and in the early stage of the dry-wet cycle, SO_4^{2-} is less intruded, mainly Cl^- in the process of invasion. It easily reacts with hydrated calcium aluminate gel first to generate chloroaluminate, which fills the pores of the TWGPC structure and improves the strength. As shown in Fig. 8(d), columnar ettringite is attached to the flake. At the same time, gypsum and flocculent chloro-aluminate exist. A large number of hydration products absorb water and expand, resulting in various dispersed stresses, including slurry aggregate loosening, TWGPC desizing, and aggregate leaking, which reduces the strength.

4. Grey system theory GM(1,1) and life prediction

The decay of concrete is caused by damage to its own structure, the decay process is the damage process of its own structure, and the decline variable is the damage amount (Liu and Wang 2000).

There are three evaluation criteria for concrete failure (China Construction Industry Press 2009): first, the relative mass is 95%; second, the relative dynamic modulus of elasticity is reduced to 60%; and third, the corrosion resistance coefficient of the compressive strength is 75%. By comparing Figs. 4, 5 and 7, it can be seen that under the action of 80 dry-wet cycles, among the 7 groups of specimens, group S10 has the lowest value of the corrosion resistance coefficient of the compressive strength relative to the dynamic modulus relative to the mass, which is 50.98%, 82.40% and 96.19%, respectively. When the compressive strength and corrosion resistance coefficient are used as the evaluation standards, the specimen has been damaged, and for the other two evaluation standards, the specimen is not damaged. Additionally, the sensitivity of the compressive strength of the corrosion resistant coefficient is greater than the sensitivity of the relative loss modulus and relative quality; therefore, based on the GM(1,1) (Wang et al. 2013) life prediction model of the grey system theory, the corrosion resistance coefficient of the compressive strength of the specimen was reasonably predicted.

The unitary first-order differential equation applicable to the whitening form of grey prediction is shown in equation (1) (Qin et al. 2021).

$$\frac{dx^{(1)}}{dt} + \alpha x^{(1)} = \beta \quad (1)$$

In equation (1), α is the development coefficient, and β is the grey action. The life prediction model based on grey system theory GM (1,1) is shown in equation (2) (Qin et al. 2021).

$$\hat{x}^{(0)}(k+1) = (1 - e^{-\alpha}) \left[\hat{x}^{(0)}(1) - \frac{\beta}{\alpha} \right] e^{-\alpha k} \quad (2)$$

$$\vec{A} = (\alpha, \beta)^T$$

The values of α and β can be obtained from vector $\vec{A}$ by the least squares method (Qin et al. 2021) and then substituted into equation (2) to obtain the expression of the corrosion resistance coefficient of the compressive strength of the specimen at time $k+1$. The prediction model is rated according to the calculated mean square error ratio C and small error probability p (Lan et al. 2007). After 40 wetting and drying cycles, the compressive strength of TWGPC reached the maximum and then began to decrease continuously. Therefore, it was taken as the initial value, and the TWGPC life and grade were predicted with the corrosion resistance coefficient of the compressive strength falling to less than 75% as the standard. The predicted results are shown in Table 4.

Table 4 Grey prediction model grade and life prediction

Group	C	p	Predicting level	Life forecast(d)		
N	0.0017	1	Level 1 (good)	0.0436	55.0173	291
S5	0.0128	1	Level 1 (good)	0.3973	79.0656	66
S10	0.0136	1	Level 1 (good)	0.4779	83.5434	56
C5	0.0036	1	Level 1 (good)	0.0900	59.5239	165
C10	0.0076	1	Level 1 (good)	0.1596	68.1646	124
CS5	0.0073	1	Level 1 (good)	0.1750	69.2104	110
CS10	0.0096	1	Level 1 (good)	0.2453	74.8791	91

As seen from Table 4, the mean square deviation ratio C of the 7 groups of TWGPC specimens was all below 0.35, and the probability of small error p was all greater than 0.95, so the prediction grade was all level 1 (good), indicating that the GM(1,1) life prediction model could well reflect the prediction and analysis of the corrosion resistance coefficient of the compressive strength of specimens with different corrosion solutions under the action of wetting-drying cycle, and the TWGPC was analysed. According to the life prediction results in Table 5, the life span of the S10 group is the lowest, and the life span of the N group is the highest, which is 5.2 times that of the S10 group. The life span of the C5 and C10 groups is 2.9 times and 2.2 times that of the S10 group and that of the CS5 and CS10 groups is 2.0 times and 1.6 times that of the S10 group, respectively. The predicted lifetime of TWGPC was the highest in clear water, the lowest in corrosive solution and Na_2SO_4 solution with the same concentration, and the lowest in NaCl solution. The predicted lifetime of the composite solution was between two single solutions. For the same corrosion solution, the higher the concentration was, the lower the predicted life, which is consistent with the results of the microstructure analysis and macroscopic mechanical tests of appearance damage. This finding verifies the feasibility of the prediction model.

Conclusion

(1) Through the appearance change, it was found that the surface of TWGPC exhibits crystallization, cracking, spalling and other phenomena with the same number of drying-wet cycles. The erosion damage of specimens in Na_2SO_4 solution was the most serious, while the erosion damage in clean water was the least serious. For the same corrosion solution, the higher the concentration was, the more serious the damage.

(2) With increasing drying and wetting cycles, the relative dynamic modulus loss of the TWGPC compressive strength and the relative mass (4 parameters) of the splitting tensile strength increased first and then decreased, finally reaching the peak value at 40 cycles. The reason for the increase is that in the corrosion solution with a low concentration, the erosion rate is slow and the crystal material is generated to fill the pores, which increases the density of TWGPC and makes the 4 parameters rise. With increasing drying and wetting cycle time, the products inside the specimen generated a swelling stress, which connected made the internal pores of TWGPC and accelerated the decline in 4 parameters.

(3) The microstructure analysis showed that under the action of wetting and drying cycles, chloroaluminate, which formed C-S-H and C-A-S-H gel flocculents in the early stage of reaction, filled the slurry-aggregate pores and improved the strength of TWGPC. In the later stage, a large number of reaction products, such as Friedel salt crystal gypsum and ettringite, absorb water and expand, which increases the internal porosity of TWGPC, desizes TWGPC and easily leaks aggregates. The strength of TWGPC is reduced.

(4) The life prediction of TWGPC in different solutions showed that the life of Na_2SO_4 solution was the lowest, the life of NaCl solution was lower, the predicted life of the mixed solution was between two single solutions (Cl^- had an inhibitory effect on SO_4^{2-} erosion of concrete), the life of clear water was the highest, and the sensitivity of TWGPC under the action of sulfate was the highest. In the same corrosion solution, the higher the concentration was, the shorter the life, which is consistent with the appearance change in the macroscopic mechanical test microstructure analysis results.

Declarations

Ethics approval and consent to participate

Not applicable

Consent for publication

Not applicable

Availability of data and materials

Not applicable

Competing interests

The authors declare that they have no competing interests.

Funding

The authors would like to thank the National Natural Science Foundation of China (No. 52074144), the Natural Science Foundation of Liaoning Province (No. 2019-MS-158), the Scientific Research Fund of Liaoning Provincial Education Department (No. LJ2020JCL001), the Key Laboratory of Mining Disaster Prevention and Control Open Fund (No. MDPC202003) and the Discipline Innovation Team of Liaoning Technical University (No. LNTU20TD-12).

Authors' contributions

All authors contributed to the conception and design of the study. Material preparation, data collection and analysis were performed by Botao Li, Yiting Wang and Hui Wang. The first draft of the manuscript was written by Qi Sun, and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Acknowledgments

The author would like to acknowledge the valuable suggestions of the editor and three anonymous reviewers.

Additionally, we would like to thank AJE (www.aje.com) for English language editing.

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Table

Table 5 is not available with this version.

Figures

Figure 1

Appearance damage after 40 cycles of drying and wetting

Figure 2

Appearance damage after 80 cycles of drying and wetting

Figure 3

Corrosion resistance coefficient of the compressive strength

Figure 4

Relative modulus of motion

Figure 5

Values of the splitting tensile strength

Figure 6

Relative mass value

(a) N

(b) S10

(c) C10

(d) CS10

Figure 7

Micromorphology under the action of 40 cycles of drying and wetting

(a) N

(b) S10

(c) C10

(d) CS10

Figure 8

Micromorphology under the action of 60 cycles of drying and wetting