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Study on mechanical properties of metakaolin based geopolymer pervious concrete

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Abstract: In this study, geopolymers were used as binder materials and large-sized aggregates as coarse aggregates to prepare pervious concrete. Design different alkali activator modulus, concentration, and coarse aggregate: geopolymer binder materials in mass, and test the physical, and mechanical properties. According to the compression test, the stress-strain curve of the metakaolin-based polymer pervious concrete was obtained, and the elastic modulus and strain were analyzed. The test results show that: with the increase of the modulus of the alkali activator, the compressive strength and splitting tensile strength show a trend of increasing first and then decreasing. The higher alkali activator concentration and the ratio of the crude aggregate to the polymer binder material are detrimental to the development of strength in pervious concrete. The mass ratio of geopolymer binder material to coarse aggregate is 1: 5, the concentration of alkaline activator is 40%, the modulus is 1.3, and the mass ratio of alkali activator solute (sodium silicate+sodium hydroxide) to metakaolin is the geopolymer pervious concrete prepared at 0.35 has higher strength and water permeability.

1. Introduction

Cement was the main building material in the world and the main source of carbon dioxide emissions[1]. Extensive use of cement materials will lead to the destruction of the ecological environment. Geopolymer materials have been studied by scholars due to their low energy consumption and wide sources. Geopolymer pervious concrete is a binder material prepared by alkali activator excitation of active materials such as metakaolin and fly ash, which is uniformly wrapped with aggregate to form a structure with connected pores. It has the characteristics of water permeability[2], sound absorption, and less pollution[3-5].

In the past studies, many experimental studies on the mix ratio, porosity, and water-cement ratio of pervious concrete prepared from cement slurry and gravel were carried out, but only a few studies involved metakaolin as a binder material to formulate pervious concrete. Arslan[6] prepared a 1: 1 alkali activator solution of sodium hydroxide and sodium silicate activator, colloid with metakaolin and 10% calcium borate matrix, and the configured geopolymer concrete had good water permeability and mechanical properties. Fly ash (FA) was used as the matrix by Simatupang[7], 10M sodium hydroxide (NaOH) solution, the mass ratio of NaOH solution to sodium silicate (Na_2SiO_3) solution was 1.0, and FA : alkaline activator in mass was 2, the prepared FA geopolymer was prepared. The maximum compressive strength of the pervious concrete was 3.0 MPa. Bian Libo[8] found through experiments that with the alkali activator modulus and alkali equivalent increasing, the compressive strength and flexural strength of pervious concrete at all ages showed a tendency of increasing and then decreasing.. Gong[9] used waste limestone powder as a binder material to prepare low-alkali planting concrete and found that it is easier to exert strength in 20% limestone powder concrete; Tarangini[10] used coarse aggregate to geopolymer gel ratio of 5, 15% of the fly ash instead of cement, the specimen has good mechanical properties.

Based on the above research, this paper uses metakaolin-based geopolymer binder material to prepare pervious concrete. By changing the mixing ratio of the binder material, the physical and mechanical properties are tested, and the optimal parameters are obtained, which offers a reference for the theoretical research and numerical analysis of the later geopolymer pervious concrete structure.

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2. Materials and methods

2.1 Materials

Coarse aggregate: The coarse aggregate used in the test was black gravel, with a particle size of 15-30 mm, an apparent density of 2714 kg/m3, a bulk density of 1398 kg/m3, a porosity of 48.6%, and a specific surface area of 0.11 m2/kg. Metakaolin (MK): It was collected from a company by Gongyi City, Henan Province, with a color of brown-red and a apparent density of 2575 kg/m^3, the specific surface area measured in the experiment was 995.4 m^2/kg. The particle size distribution of aggregate and metakaolin is demonstrated in Figure 1. Alkali activator solution: The alkali activator solution used in the test was prepared from NaOH, Na_2SiO_3 and deionized water and was used at room temperature. NaOH used in the configuration process was an industrial flake alkali produced by Inner Mongolia Junzheng Company, and its purity was 95%. Powdered Na_2SiO_3 came from Xi'an Huachang Water Glass Company. Its SiO_2 and Na_2O content were respectively 60.10% and 21.53%.

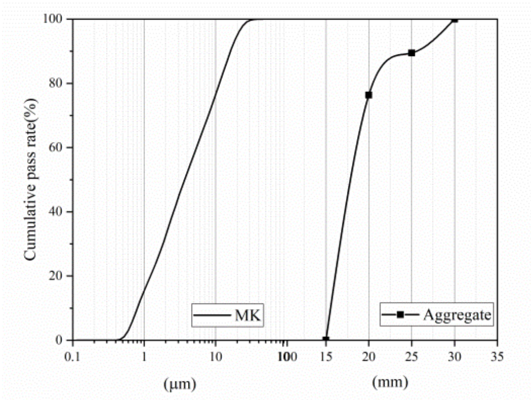

Figure1 Distribution of metakaolin particles and aggregates.

2.2 Test scheme

The mass ratio of coarse aggregate to the pervious concrete [11] was 75% in mass, and the quantity of coarse aggregate was 1440 kg/m^3. Initial pre-tests showed that when the ratio of aggregate to the geopolymer binder materials (the sum of MK, NaOH, and Na_2SiO_3) in mass was selected as 4.5, there is a small amount of sedimentation when the specimen is de-molded. When the modulus is 1.5 and the concentration is 50%, the geopolymer gel has a rapid setting phenomenon, and the geopolymer binder material cannot wrap the aggregate. Therefore, in this study, the alkali activator modulus were 1.1, 1.3, and 1.5 (the corresponding mass ratio of sodium silicate to sodium hydroxide is 2.24, 3, 4), the concentration is 40%, 45%, the alkali activator solute and metakaolin the ratios were selected as 0.35 and 0.4, and the ratios of aggregates and geopolymer binder materials were selected as 5 and 6. Perform a full-factor analysis of modulus and concentration, and the test scheme plan was shown in Table1.

The geopolymer pervious concrete was prepared by wrapping binder material with aggregate. The MK and alkaline activator were mixed with a hand-held mixer to very high flowability, then the geopolymer binder material was poured into the blender and the aggregate was mixed together for 3 minutes. The mixed concrete was loaded into the mold in three batches, and manually vibrated 25 times with an iron bar and finally flattened. The specimen and mold were covered with plastic film and placed in a curing chamber at 95% humidity and (20±2) °C. The specimen was cured for 24 hours and the mold was removed. After 24 hours of curing, the specimens were formed and the molds were removed. The specimens were cured in the maintenance room for 28 days, and the casting sizes of permeable concrete specimens were 100 mm × 100 mm × 100 mm, 100 mm × 100 mm × 400 mm, and Φ100 mm × 100 mm.

Table1 Concrete mix proportion of each group. (unit: Kg/m^3)

No.	ratio	Modulus (M)	Concentration (%)	Metakaolin	Sodium silicate	Sodium hydroxide	Water	Ratio
G1	5	1.1	40	213.3	51.6	23.1	112.0	0.35
G2	5	1.1	45	213.3	51.6	23.1	91.3	0.35
G3	5	1.3	40	213.3	56.0	18.7	112.0	0.35
G4	5	1.3	45	213.3	56.0	18.7	91.3	0.35
G5	5	1.5	40	213.3	59.7	15.0	112.0	0.35
G6	5	1.5	45	213.3	59.7	15.0	91.3	0.35
G7	6	1.1	40	171.4	47.4	21.2	103.0	0.4
G8	6	1.1	45	171.4	47.4	21.2	83.8	0.4
G9	6	1.3	40	171.4	51.4	17.1	103.0	0.4
G10	6	1.3	45	171.4	51.4	17.1	83.8	0.4
G11	6	1.5	40	171.4	54.9	13.7	103.0	0.4
G12	6	1.5	45	171.4	54.9	13.7	83.8	0.4

2.3 Experimental methods

The measurement method of test porosity (e) is: the specimen is placed in the oven at 80 °C and baked until 24h, and then the quality of the specimen m_1(g) is weighed. Measure the mass m_2(g) of the specimen in the water and the bulk of the specimen V (cm^3), which is the density of the water ρ (g/cm^3). The three specimens are grouped and averaged to obtain the porosity of the specimens. The porosity is calculated as shown in Equation 1.

$$e=\left(1-\frac{m_1-m_2}{\rho V}\right)\times 100\% \quad (1)$$

As shown in Figure2, the water permeability of the samples was metrologied using the constant head method. The coefficient of permeability was calculated according to Darcis' law (Equation 2).

$$k=\frac{aL}{At}\times\ln\frac{h_1}{h_2} \quad (2)$$

Where: k is the permeability coefficient (mm/s), a is the cross-sectional area of pipe (mm^2), A is the cross-sectional area of the cylindrical sample (mm^2), L is the length of the sample (mm), t is the time for the water head to change from h_1 to h_2, h_1 is the initial water head (mm), and h_2 is the final water head (mm), and h_1/h_2=150 mm.

Figure 2 Porosity testing instrument and water permeability coefficient test device.

Mechanical properties test methods: The size of the split tensile strength specimen was 100mm×100 mm×100 mm, the loading rate was 0.5 kN/s, the flexural strength test was carried out by a three-point bending test, and the size of the specimen was 100 mm×100 mm×400 mm, and the loading rate during the test was 0.2kN/s. The compressive strength test uses a TAW-2000 rock triaxial testing machine to obtain the load-displacement curve of the geopolymer pervious concrete, the loading rate is 0.5 mm/min.

3. Results and analysis

3.1 Measurement results of porosity and permeability coefficient

Figure 3 shows that the target porosity calculated according to the absolute volume method[12] fluctuates around 22%-26%. The higher the porosity, the larger the water permeability coefficient, but the actual porosity is different from the target porosity. The porosity calculated by the absolute volume method is an absolute value, which is different from the actual value. In the experiment, the particle size of the aggregate is larger, and the thickness of the gel encapsulated by the aggregate leads to the difference in porosity. Among them, the coarse aggregate to geopolymer binder material ratio affects the thickness of the coating and then affects the water permeability and porosity, the smaller the coarse aggregate to geopolymer binder material ratio, the stronger the cohesion between the aggregates. The thickness of the colloid-wrapped aggregate increases to reduce the connectivity between the upper and lower layers of the concrete structure, this results in a reduced permeability coefficient of the pervious concrete.

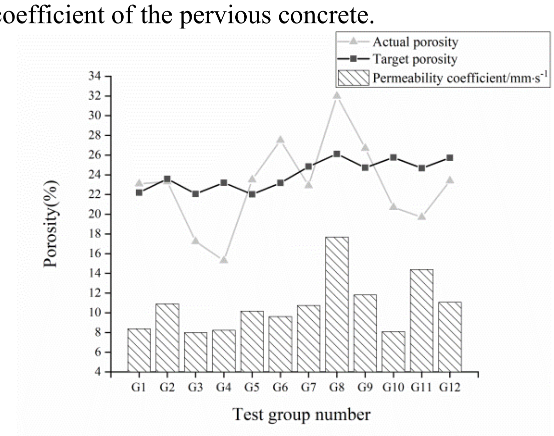

Figure 3 Test results of porosity and permeability coefficient.

3.2 Analysis of flexural strength and split tensile strength

Figure 4 shows the flexural strength of geopolymer pervious concrete specimens, with a maximum of 1.6 MPa. The geopolymer gel only wraps the stone without other fine aggregates. The pores between the aggregates are large and the friction force is small, when the maximum failure load is reached, it has an obvious brittle failure. A slight sound was heard before the failure of the specimen, and the failed specimen was completely divided into two halves, and the failed specimen was in good agreement. Figure 5 shows that the splitting tensile strength also increases with the increase of curing age. In the splitting tensile strength results, the G3 specimen exhibits better splitting resistance, which is 1.5 times that of the G9 specimen, and the greater the coarse aggregate to geopolymer gel ratio the splitting tensile strength is lower. Secondly, the coarse aggregate to geopolymer gel ratio is relatively small, the thickness of the slurry coating is thicker, and the strength develops faster. Geopolymer pervious concrete has an early strength effect, and the early splitting tensile strength increases significantly, and the later strength increases slowly. The 7d strength of geopolymer pervious concrete is 70%-90% of the 28d strength, this is because the active ingredient in metakaolin and the hydration product silicate ion generated by the alkali activator form a stable chemical substance. During the dissolution process, metakaolin releases a 1: 1 silicon-alumina substance, and the substance has been fully reacted, the early improvement of pervious concrete is large, and its network molecular structure is not destroyed when cured for 28 days, and the strength is still improved, but the improved speed is slow.

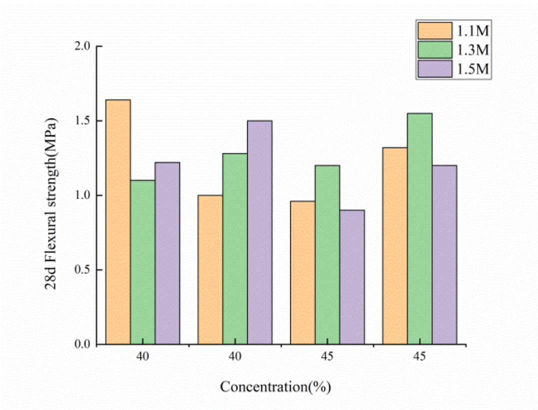

Figure 4 28-day flexural strength of different modulus.

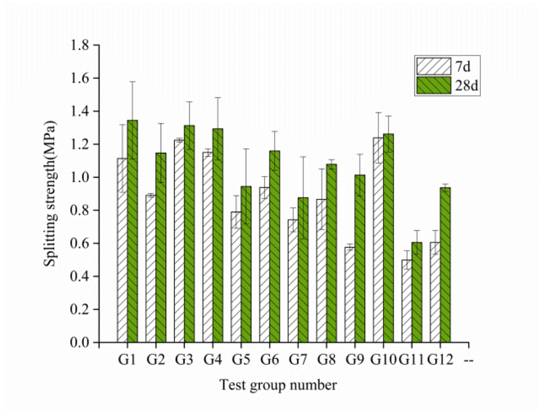

Figure 5 Test results of splitting tensile strength.

Figure 6 shows that the splitting tensile strength varies with the modulus under different coarse aggregate to geopolymer gel ratios and concentrations. Generally speaking, with the increase of the modulus, the splitting tensile strength of geopolymer pervious concrete with the same bone-cement ratio first increased and then decreased. In the 7-day split tensile strength result chart, the split tensile strength of the specimen decreased gradually with the increase of the modulus when the coarse aggregate to geopolymer gel ratio was 6 and the concentration was 40%. Due to the relatively small amount of geopolymer binder material, excess hydroxide ions are generated as the modulus increases, hindering the development of its strength. When the increase in the modulus of the alkali activator, the splitting tensile strength of the test groups is higher when the concentration is 40%. The main reason is that the content of sodium silicate and hydroxide increases, which interacts with SiO2 in metakaolin to form a large number of tetrahedral agglomeration bonds, which are tightly wrapped around the stone, and improve specimen strength[13].

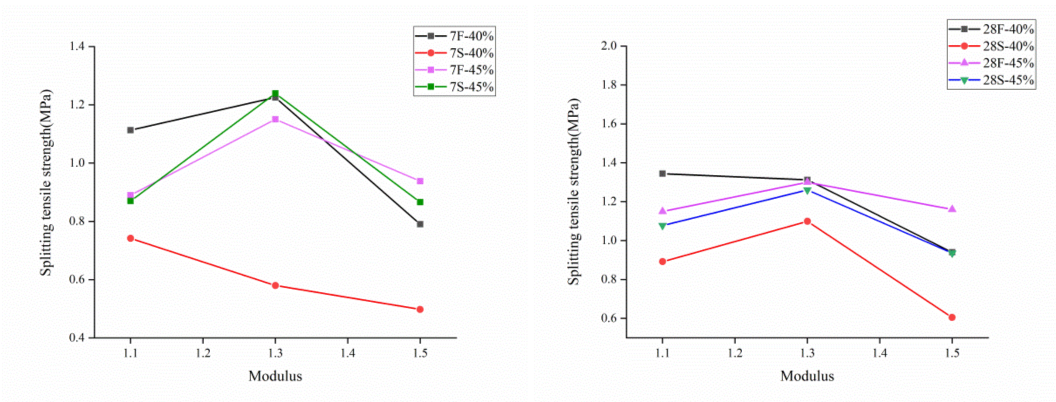

Figure 6 7-day and 28-day splitting tensile strength under different modulus concentrations.

3.3 Analysis of compressive strength

According to Figure7, it can be seen that the compressive strength increases with the increase of curing age, and the compressive strength of the pervious concrete specimens is generally small when large-sized aggregates are used. The 28d compressive strength of the G3 specimen is up to 9.3 MPa, in the strength test of 7d and 28d, the compressive strength first increased and then decreased with the increase of modulus, and the compressive strength was the highest when the concentration was 40% and the modulus was 1.3. When the modulus exceeds 1.3, the compressive strength does not increase significantly with the increase of modulus and concentration, this is due to the increase in modulus, the larger proportion of sodium silicate aqueous solution, and the larger content of silicon ions in the remaining sodium silicate aqueous solution, which hinders the dissolution of metakaolin to form silicon-alumina substances. This leads to the occurrence of curing sequence problems in the generation of silicon-oxygen and aluminum-oxygen tetrahedral three-dimensional network geopolymers, which in turn affects the formation of the system structure, resulting in a decrease in compressive strength. When the modulus is 1.1, too high hydroxide ions lead to rapid precipitation of aluminosilicate in the early stage and hinder the utilization of Si and Al in the mixture in the geopolymer polymerization process. The continuous increase of the alkali concentration inhibits the dissolution of the raw materials and causes the raw materials to precipitate, resulting in a decrease in strength. Figure7 and Figure 8 show that there are differences in the results of metakaolin-based geopolymer pervious concrete with different coarse aggregate to geopolymer binder material ratios. The larger coarse aggregate: geopolymer binder, the lower the compressive strength, and the 28d compressive strength of G3 specimen is 1.16 time of G9 specimen, and the smaller coarse aggregate: geopolymer binder, the more the geopolymer gel can be packed around the aggregate to exert its strength. Secondly, the smaller coarse aggregate: geopolymer binder, the lower the porosity of the specimen, the better the mechanical occlusion, the stronger the bond between aggregate and aggregate, and the better it can defer the generation of cracks under the load.

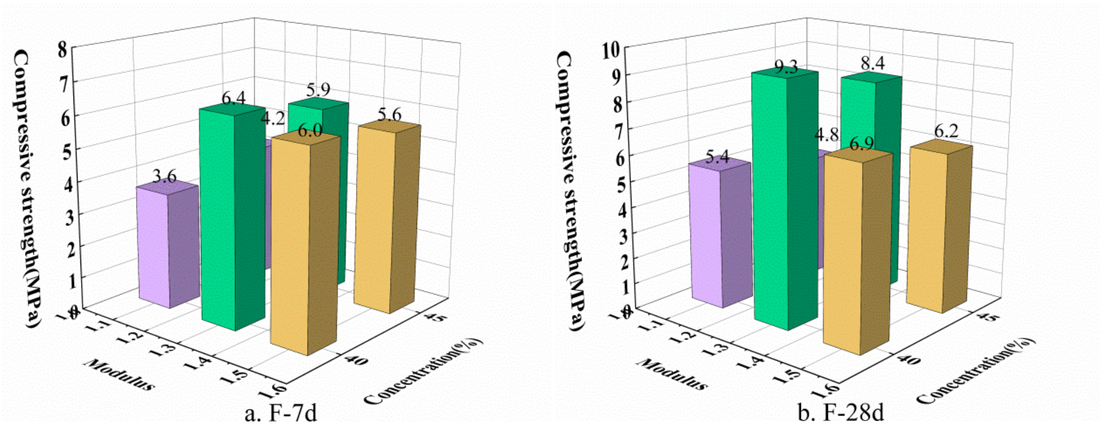

Figure 7 Compressive strength when the coarse aggregate to geopolymer gel ratio is 5.

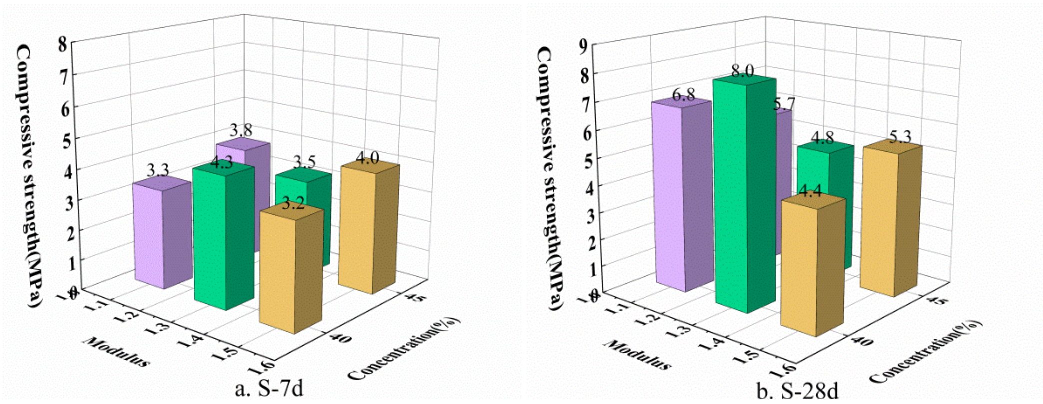

Figure 8 Compressive strength when the coarse aggregate to geopolymer gel ratio is 6.

4. Conclusion

As the modulus of the alkali activator increases, the strength of the geopolymer pervious concrete first increases and then decreases, and the bone-cement ratio has a significant effect on the strength results.

(1) The tests revealed that the mass ratio of geopolymer binder to coarse aggregate was 1:5, the mass ratio of alkaline activator solute to metakaolin was 0.35, and the concentration of alkaline activator was 40%, among which sodium silicate (Na2SiO3) and sodium hydroxide (The geopolymer pervious concrete prepared when the mass ratio of the NaOH) was 3 had higher strength, water permeability and slurry coating thickness.

(2) When the geopolymer pervious concrete fails, cracks appear at the interface between the gel and the aggregate, and the lower porosity can resist the development of cracks. The density of pervious concrete is relatively concentrated between 1.8-1.9 g/cm3, and there is a good correlation between density and porosity.

References

1. Yang, K.; Jung, Y.; Cho, M.; Tae, S. (2015) Effect of Supplementary Cementitious Materials On Reduction of CO2 Emissions From Concrete. J. Clean. Prod., 103, 774-783.
2. Harada, S.; Yanbe, M. (2018) Adsorption by and Artificial Release of Zinc and Lead From Porous Concrete for Recycling of Adsorbed Zinc and Lead and of Porous Concrete to Reduce Urban Non-Point Heavy Metal Runoff. Chemosphere, 197, 451-456.
3. Yao, X.; Wang, W.; Liu, M.; Yao, Y.; Wu, S. (2019) Synergistic Use of Industrial Solid Waste Mixtures to Prepare Ready-To-Use Lightweight Porous Concrete. J. Clean. Prod., 211, 1034-1043.
4. Govedarica, O.; Aškrabić, M.; Hadnađev-Kostić, M.; Vulić, T.; Lekić, B.; Rajaković-Ognjanović, V.; Zakić, D. (2022) Evaluation of Solidified Wastewater Treatment Sludge as a Potential SCM in Pervious Concrete Pavements. Materials, 15 (14), 4919.
5. Li, S.; Yin, J.; Zhang, G. (2020) Experimental Investigation On Optimization of Vegetation Performance of Porous Sea Sand Concrete Mixtures by pH Adjustment. Constr. Build. Mater., 249, 118775.
6. Arslan, A.A.; Uysal, M.; Yılmaz, A.; Al-mashhadani, M.M.; Canpolat, O.; Şahin, F.; Aygörmez, Y. (2019) Influence of Wetting-Drying Curing System On the Performance of Fiber Reinforced Metakaolin-Based Geopolymer Composites. Constr. Build. Mater., 225, 909-926.
7. Simatupang, P.H.; Adu, M.A.J.; Sadukh, Y.M.I.; (2019) Jonbi Pervious Low-Calcium Fly Ash Geopolymer Concrete Using Gap-Graded Limestone Coarse Aggregates in Ambient Curing. IOP conference series. Materials Science and Engineerin, 669 (1), 12023.
8. Bian, B.; Dong S.; Tang Z. (2020) Basic Properties of Alkali Activated Slag/Fly Ash Pervious Concrete. Materials reports, 34 (S2), 1299-1303.
9. Gong, C.; Zhou, X.; Ji, L.; Dai, W.; Lu, L.; Cheng, X. (2018) Effects of Limestone Powders On Pore Structure and Physiological Characteristics of Planting Concrete with Sulfoaluminate Cement. Constr. Build. Mater., 162, 314-320.
10. Tarangini, D.; Abhilash, A.; Sravana, P.; Srinivasa Rao, P. (2022) Effect of Fly Ash On Properties of Gap Graded Concrete. Materials Today: Proceedings, 51, 475-479.
11. Lamond J., F., Pielert J., H. (2006) Significance of Tests and Properties of Concrete and Concrete-making Materials. ASTM International, West Conshohocken, PA, USA
12. Technical Specification for Pervious Cement Concrete Pavement: CJJ/T 135-2009 [S]. Ministry of Housing and Urban-Rural Development of the People's Republic of China.
13. Cui, C.; Peng, H.; Liu, Y.; Zhang, R.; Cai, S; Peng, Y. (2017) Influence of GGBFS content and activator modulus on curing of metakaolin based geopolymer at ambient temperature. Journal of Building Materials, 20 (04), 535-542.