Current research status and application prospects of permeability and mechanical properties of pervious concrete

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Abstract. Permeable concrete, characterized by continuous porosity, offers excellent properties such as breathability, water permeability, sound absorption, water purification, and environmental enhancement. This paper comprehensively reviews previous research on permeable concrete, encompassing studies on mix design, workability, mechanical properties, drainage performance, sound absorption, and durability. It also discusses improvement measures and application prospects. Research indicates that the performance of permeable concrete is influenced by factors such as mix design, material composition, and construction techniques. Optimizing mix design, modifying material composition, and enhancing workability and mechanical properties can further improve the performance of permeable concrete. Permeable concrete shows broad application prospects in road engineering, landscaping, and environmental engineering, but further research and standardization are needed to support its widespread adoption.

Keywords: Permeable concrete, mix design, mechanical properties, drainage performance, sound absorption, durability.

1. Introduction

Compared to conventional concrete, permeable concrete possesses numerous outstanding properties such as breathability, water permeability, sound absorption, water purification, improvement of surface soil environments, mitigation of surface runoff, and alleviation of urban heat island effects. Due to these excellent characteristics, permeable concrete has garnered significant attention within the context of sustainable development and ecological balance [1]. Developed countries like Europe, the United States, Japan, and South Korea began researching and developing permeable concrete over 50 years ago, and it has since been widely applied in various fields such as road engineering, landscaping, and environmental engineering, yielding positive societal, environmental, and ecological outcomes [2]. Research on permeable concrete in China started relatively late, but since 1995, numerous domestic research teams have achieved significant advancements in this area. In practical engineering applications, permeable concrete has been successfully employed in projects such as the Beijing Olympic Park and the Shanghai World Expo Park, showcasing its excellent permeability and visual effects. However, research and application of permeable concrete still face various challenges, including technological maturity, standardization issues, and fundamental theoretical aspects [3]. Therefore, further research into permeable concrete is not only necessary but also a future trend in research development.

2. Factors Influencing Basic Properties of Permeable Concrete

2.1. Aggregate

Numerous researchers have conducted extensive work on the mix design and experimental research of permeable concrete using orthogonal experimental methods. The main research content and achievements are as follows: Analyzing the mix design methods of permeable concrete, comparing different mix design methods, and providing examples of basic mix design using volumetric methods. Orthogonal experimental methods were employed for the mix design of permeable concrete, analyzing and comparing the results of each test group. The study discussed the primary and secondary factors affecting the compressive strength and permeability of permeable concrete, and identified the optimal mix design. Compressive strength, porosity, and permeability coefficient of permeable concrete were determined. Methods to improve the strength of permeable concrete while achieving basic permeability were studied, discussing the effects of sand ratio and molding methods on its performance. Relationships between porosity and permeability coefficient, porosity and compressive strength, and permeability coefficient and compressive strength of permeable concrete were researched, providing fitting relationships, and conducting multivariate linear regression analysis on various experimental factors [4]. Finding suitable material compositions for high-performance permeable concrete mix design can fundamentally improve its mechanical properties. Based on the viewpoint that concrete is a biphasic material, rheological tests were conducted to understand the rheological properties of the matrix, followed by uniformly adding aggregate fillers to explore the composition and properties of the resulting permeable concrete [5].

2.2. Workability

Workability significantly influences the cost and quality of permeable concrete, serving as a key factor in determining the difficulty of construction operations and engineering quality. Therefore, good workability is essential for freshly mixed permeable concrete. To ensure good workability of permeable concrete, it is crucial to master appropriate mix proportions and select suitable raw materials, admixtures, and additives [6]. Moreover, mixing, pouring, compaction, and curing during construction also significantly affect workability and require strict control to ensure the quality of permeable concrete. Through detailed exploration and optimization of these aspects, we can enhance the workability of permeable concrete, reduce construction difficulty and costs, and improve engineering quality [7]. Additionally, the durability of the designed concrete should not be too low, as frost resistance is a critical factor determining the service life of concrete in cold regions [8].

Yang Lixiang and other scholars compared the effects of different water-to-binder ratios and the amount of admixture on the fluidity of cementitious material slurry, exploring the coupling effect between slurry fluidity and the mass ratio of medium sand to slurry on the thickness variation of recycled coarse aggregate-coated mortar. In the study, mathematical models were established to relate the fluidity of cementitious material slurry with the amount of admixture, the thickness of recycled coarse aggregate-coated mortar with slurry fluidity, and the mass ratio of medium sand to slurry. These models were then applied to the mix design of pervious concrete [9].

2.3. Mechanical Properties

Due to the unique porous structure of permeable concrete, the bonding area between cement paste and aggregates, as well as the contact points between aggregates, are reduced compared to conventional concrete (CC). This generally leads to a significant reduction in strength of permeable concrete. Studies have shown that the main factors influencing the strength of permeable concrete include concrete porosity, water-cement ratio (w/cm), paste characteristics, coarse aggregate particle size, and volume content [10]. To optimize the mechanical properties of permeable concrete, researchers both domestically and internationally have conducted extensive specialized research. One method used to simulate the mechanical behavior of permeable concrete is a stochastic modeling approach based on a new extension of the lattice discrete particle model. Selected digital images of internal mesostructures obtained from physical specimens are used to investigate material characteristics and generate statistically representative descriptions of pore networks. This process estimates statistical characteristics of mesostructures and utilizes spatially correlated random field samples to numerically reproduce the distribution of large connected pores in materials [11].

Permeable concrete is manufactured by adding paste that is insufficient to fill the voids in the aggregates, thereby creating drainage channels within the concrete. However, aggregate expansion increases the void volume in aggregates after adding paste, which has been overlooked in previous studies. Furthermore, the impact of unfilled voids on the performance of permeable concrete remains unclear. In this study, researchers investigated the flowability and adhesion of paste, aggregate expansion, and the effects of paste properties, aggregate expansion, water film thickness (WFT), and paste film thickness (PFT) on the permeability and strength of permeable concrete. The results indicate that paste properties, aggregate expansion, WFT, and PFT play a primary role in the design of permeable concrete and are therefore critical factors to consider [12].

2.4. Drainage Performance

Tan Yan utilized two-dimensional scanning and image recognition technology to study the pore structure of specimens at different depths. Using fine particles with a diameter of 0-0.6 mm such as stone powder particles, cement mortar particles, and soil particles as blocking materials, the specimens were blocked in batches, and the water permeability loss was recorded. Finally, three methods—cleaning with water, vacuum suction, and high-pressure water jet—were used to conduct water permeability recovery tests on the specimens to simulate their use under periodic cleaning and maintenance conditions. The research findings indicate:

(1) The porosity at a depth of 20 mm in permeable concrete is approximately 10% higher than that at depths of 40 mm, 60 mm, and 80 mm.

(2) Each additional 10 g of blocking material results in a water permeability loss of 30%-50%, with the most severe water permeability loss caused by the initial blocking.

(3) Under the influence of the same blocking material, different permeable specimens exhibit similar variations in water permeability coefficient during the blocking process, and this pattern can be used to predict the blocking time of specimens with higher water permeability coefficients.

(4) For blockages caused by stone powder particles and cement mortar particles, the high-pressure water jet washing method shows the best effectiveness, increasing the water recovery rate by 22.7%.

(5) For blockages caused by soil particles, vacuum suction is not advisable, and cleaning with water achieves the same recovery effect as the high-pressure water jet [13].

2.5. Sound Absorption and Noise Reduction Performance

Porous concrete has advantages in noise reduction. When sound waves propagate through pores, deformation and attenuation occur, thereby reducing noise. Further research indicates that porous concrete with larger porosity exhibits higher sound absorption coefficients. Within the porosity range of 15% to 30%, porous concrete provides good noise reduction performance. Moreover, pore size significantly affects noise reduction behavior, with an optimal pore size existing for noise reduction. Increasing the tortuosity of porous concrete enhances sound energy absorption through internal friction, thus reducing noise. The maximum sound absorption coefficient shows a linear relationship with pore connectivity. Furthermore, an increase in pore connectivity leads to an increase in maximum sound absorption [14].

3. Construction Techniques

Advanced construction techniques can reduce construction time and materials, improve construction quality, minimize environmental impact, enhance structural durability and lifespan, and lower overall

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construction costs [15]. Compaction is a fundamental step in the production of permeable concrete, affecting its mechanical and hydraulic performance. Mikami evaluated its influence on porosity, mechanical strength, and permeability. Increasing compaction energy proportionally reduces porosity. It was observed that compressive strength increased from 17% to 36%. However, permeability decreases proportionally, dropping by 0.2 to 0.4 cm/s. Three-layer compaction results in a more uniform vertical distribution of porosity compared to two-layer compaction. While aggregate/cement ratio is the most significant parameter, compaction energy should also be considered in the mix design of permeable concrete. Although increasing compaction energy can enhance mechanical strength, excessive compaction can cause aggregate fracture, reducing both mechanical and hydraulic performance [16]. There exists a relationship model among porosity, consistency, and compaction time for permeable concrete. Chilmon's research found that compaction time and material composition significantly influence porosity and all other performance aspects of permeable concrete within assumed variable ranges [17]. Permeable mixes prepared with recycled coarse aggregates achieve similar compressive strength and higher porosity. River sand coarse aggregates exhibit better abrasion resistance, while coarse limestone aggregates perform better in drying shrinkage [18]. By optimizing pore structure and improving mix design, the strength and permeability of permeable concrete can be enhanced. Results indicate that although overall porosity decreases by 5% after optimizing pore structure, the porosity of large and medium pores changes minimally, while that of small pores decreases significantly, ultimately increasing the average pore size. Adding steel slag not only reduces small pore size but also increases compressive strength [19].

Over time, permeable concrete loses its permeability due to clogging. Silva RG da evaluated the effectiveness of periodic cleaning using blowers, demonstrating that periodic cleaning with blowers is effective. There were no significant statistical differences in permeability between monthly and weekly cleaning. Therefore, monthly maintenance is most suitable for maintaining the efficiency of permeable pavements over time [20].

4. Improvement Measures

In pursuit of higher performance, many scholars have explored various new types of permeable concrete. Wang Cen's research results indicate that the addition of recycled aggregates significantly affects the mechanical properties of permeable concrete. When the proportion of recycled aggregates does not exceed 50%, the splitting tensile strength, flexural strength, compressive strength, and uniaxial tensile strength of permeable concrete decrease by approximately 30%. When the proportion of recycled aggregates exceeds 50%, the mechanical parameters of permeable concrete noticeably decline. However, using 50% recycled aggregates meets specifications for compressive strength, splitting tensile strength, flexural strength, and uniaxial tensile strength [21].

Zhao Jing's SEM analysis found significant pores in permeable concrete without epoxy resin. When epoxy resin content reaches 3% (by mass fraction), there are virtually no visible pore cracks, and the fracture surface appears smoother. This indicates that adding an appropriate amount of epoxy resin can significantly improve the microstructure of permeable concrete, enhancing the bonding between hydration products and thereby improving its mechanical properties [22].

Fiber-modified recycled aggregate permeable concrete shows potential in addressing urban flooding, heat island effects, and noise issues. Chen Shoukai, in his research, improved the base mix ratio by incorporating different fiber materials (short-cut basalt fiber, short-cut carbon fiber, and polypropylene fiber), preparing 16 mix samples, and evaluating their compressive strength, flexural strength, porosity, and permeability coefficient. The study results demonstrate that fiber incorporation effectively enhances the compressive strength, flexural strength, and tensile-compressive ratio of recycled aggregate permeable concrete, with better improvement observed in flexural strength than in compressive strength [23]. Xin Zhipeng and other scholars found that fly ash significantly enhances the later-stage strength of recycled aggregate permeable concrete. With increasing fly ash content, the mechanical performance and freeze-thaw resistance of permeable concrete improve, while its permeability decreases. However, excessive fly ash reduces the permeability of recycled permeable concrete to a large extent [24].

Regarding aggregates, researchers used the simplex centroid design method to optimize the ternary cementitious system composed of cement, fly ash, and silica fume to obtain a high-performance cementitious matrix. They then analyzed the effects of high-performance cementitious matrix and recycled aggregate mass fractions (0%, 30%, and 50%) on the mechanical properties and durability of permeable concrete. Experimental results show that using high-performance cementitious materials significantly enhances the compressive strength and freeze-thaw durability of recycled aggregate permeable concrete, while meeting permeability requirements [25][26].

To address the issue of high elastic modulus and low freeze-thaw resistance in ordinary permeable concrete, Yan Chaoqun proposed using modified waste rubber to enhance the performance of permeable concrete. Compared to ordinary permeable concrete, although material costs slightly increase, modified waste rubber permeable concrete exhibits superior performance in terms of service life, durability, and comfort, thereby offering better economic benefits [27]. Kanghao Tan utilized biochar (BC) as a partial replacement for cement added to permeable concrete, reducing cement usage while improving the concrete’s moisture and heat characteristics. This strategy also helps increase concrete strength and water absorption and improves cooling performance through evaporative cooling, while also reducing CO2 emissions to some extent [28]. The use of pumice powder typically reduces the initial strength of concrete; however, using 10-25% pumice can increase mechanical strength after 90 days [29].

5. Application Prospects

Due to its environmental benefits, permeable concrete is increasingly used in various infrastructures, including road surfaces and overlays in areas experiencing heavy traffic and cold weather conditions. These expanded applications require permeable concrete to exhibit excellent strength and durability [30].

Traditional concrete road surfaces are impermeable with very poor drainage performance. Material selection directly affects the drainage performance of road construction, thereby influencing urban residents’ commuting experiences. To enhance road surface drainage, construction units need to thoroughly consider road materials. Permeable concrete, with its porous nature, ease of construction, lightweight properties, and excellent permeability, shows greater potential and advantages compared to traditional concrete materials. In urban water cycling, permeable concrete can play a crucial role, leading to its increasingly widespread application [31][32][33]. Applying permeable concrete in road design effectively resolves drainage issues and mitigates urban flooding. Additionally, permeable concrete contributes to reducing urban heat island effects, decreasing stormwater runoff pollution, and enhancing groundwater recharge [34].

Existing pedestrian walkways on bridges often suffer from inadequate drainage and water pooling issues. Using permeable concrete can effectively mitigate these issues by allowing excess water to drain through its internal pores [35]. In the construction of modern gardens, permeable concrete maximizes the utilization of rainwater resources, creating favorable conditions for ecological conservation in modern garden environments and effectively alleviating pressure on garden drainage systems [36]. Permeable concrete has potential in soil conservation; low-alkalinity vegetation permeable concrete, combined with a grid beam structure system, effectively enhances stability and strength between vegetation and underlying soil. Innovatively reducing concrete alkalinity by adding a specially designed admixture to cement slurry can improve plant adaptability [37].

Permeable Paving Systems (PPS) represent an alternative technology suitable for simultaneously mitigating urban flooding and urban heat islands (UHI). Permeable concrete serves as the core material for this paving system [38]. It efficiently replenishes groundwater resources by directly draining rainwater from natural ground surfaces that cannot infiltrate underground directly or indirectly, thereby reducing water resource issues caused by sharp declines in groundwater levels in urban areas. Moreover, it more efficiently reduces harmful additives such as oil compounds on urban surfaces, thereby protecting urban groundwater resources more reasonably, maintaining stable ecological water volumes, and effectively mitigating urban heat island effects [39].

Shabalala evaluated the water quality of acid mine drainage (AMD) treated with permeable concrete (PERVC) technology through batch experiments. The study proposed an innovative application of PERVC as a permeable reactive barrier liner in evaporation ponds [40].

6. Conclusion

Due to its unique properties, permeable concrete has experienced rapid development in developed countries such as Europe, America, Japan, and Korea. However, research on permeable concrete in China started relatively late, and its theoretical research and application still require improvement, with many mechanisms yet to be clarified. Future research should focus on the following aspects:

(1) Systematically study the microstructure and macrostructure of permeable concrete materials to further explain their performance and physical-mechanical properties, enhancing compressive strength, flexural strength, and durability.

(2) Analyze the reasons for the decline in permeability function of permeable concrete and its influencing factors, research corresponding solutions, and assess their feasibility.

(3) Conduct field experiments to evaluate the ecological and environmental indicators of permeable concrete, such as air permeability, water permeability, sound absorption and noise reduction, and water purification, promoting its application in the field of ecological and environmental protection.

(4) Develop relevant specifications and standards covering the mix design, construction, maintenance, and management of permeable concrete to promote its nationwide application.

Through in-depth research and improvement in these areas, we can advance the research and application of permeable concrete in China, accelerate its widespread use nationwide, and ultimately improve urban ecological environments, enhance livability, and optimize water resource management systems.

References

[1] Wang, Y., Yan, B., & Li, C. L. (2017). A review on preparation and properties of pervious concrete. Bulletin of the Chinese Ceramic Society, 36(03), 864-869. https://doi.org/10.16552/j.cnki.issn1001-1625.2017.03.018.
[2] COSTA FBP, LORENZI A, HASELBACH L, SILVA FILHO LCP. Best practices for pervious concrete mix design and laboratory tests. Rev IBRACON Estrut Mater [Internet].
[3] Zhang, X. C., Yin, J., & Chi, Y. (2010). A review on properties of pervious concrete. Concrete, (12), 47-50.
[4] Sun, H. Y. (2017). Mix design and experimental study of pervious concrete based on orthogonal experimental method (Master's thesis). Southwest Jiaotong University.
[5] Tang, C.-W., Cheng, C.-K., & Tsai, C.-Y. (2019). Mix design and mechanical properties of high-performance pervious concrete. Materials, 12, 2577.
[6] Chen, H., Du, Z. Y., Ding, H. Z., et al. (2023). Study on the influence of external admixtures on properties of pervious concrete. Chongqing Architecture, 22(03), 42-45.
[7] Zhang, C., Ren, P. P., Deng, P., et al. (2023). Mechanical properties and durability of pervious concrete with recycled aggregate. Journal of Hunan University (Natural Sciences), 50(03), 185-194.
[8] Wang, R. J., Hu, Z. Y., Li, Y., Wang, K., & Zhang, H. (2022). Review on the deterioration and approaches to enhance the durability of concrete in the freeze–thaw environment, Construction and Building Materials, Volume 321, 126371, ISSN 0950-0618.
[9] Yang, L. X., Song, X. F., Lu, M. R., et al. (2022). Mix design method of sand-containing pervious concrete based on thickness of slurry covering coarse recycled aggregate. Materials Review, 36(04), 115-121.
[10] Chen, Y., Wang, K. J., Wang, X. H., Zhou, W. F. (2013). Strength, fracture and fatigue of pervious concrete. Construction and Building Materials, 42, 97-104.
[11] Alessandro Fascetti, Sonoko Ichimaru, John E. Bolander, Stochastic lattice discrete particle modeling of fracture in pervious concrete DOI: 10.1111/mice.12816

[12] Li, L. G., Feng, J. J., Lu, Z. C., Xie, H. Z., Xiao, B. F., Kwan, A. K. H., Jiao, C. J. (2022). Effects of aggregate bulking and film thicknesses on water permeability and strength of pervious concrete. Powder Technology, 396(Part B), 743-753.
[13] Tan, Y., Yi, C. G., Hu, A. D., et al. (2021). Study on clogging and permeability recovery of pervious concrete pavement. Journal of Central South University (Science and Technology), 52(07), 2480-2490.
[14] Yu, F., Guo, J. X., Liu, J., Cai, H., Huang, Y. B. (2023). A review of the pore structure of pervious concrete: Analyzing method, characterization parameters and the effect on performance. Construction and Building Materials, 365, 129971.
[15] Sverak, T., Špak, M. (2016). Comparison of conventional and advanced concrete technologies in terms of construction efficiency. SN-1687-8434.
[16] Mikami, R. J., Pieralisi, R., & Pereira, E. (2024). Influence of compaction energy on pervious concrete properties and vertical porosity distribution. Revista IBRACON De Estruturas E Materiais, 17(2), e17203. 2018Sep;11(5):1151–9.
[17] Chilmon, K., Jaworska, B., Kalinowski, M., Jackiewicz-Rek, W., Podkoń, A. (2023). Significance of vibration time in developing properties of precast pervious concrete. Materials, 16, 6239.
[18] Demet Yavuz; Şemsi Yazıcı, Experimental study of aggregate size and gradation on pervious concretes' mechanic, hydraulic, and surface properties, 10.1002/SUCO.202200234
[19] Yu, F., Guo, J. X., Li, Z., Huang, Y. B. (n.d.). Enhancing both strength and permeability of perviousconcrete by optimizing pore structure: An experimental Study, DOI: 10.1002/suco.202201204
[20] Silva RG da, Albuquerque M da CF de, Bortoletto M, Spósito F de A, Gonçalves AC, Alcântara MA de M. The Effect of Periodic Maintenance on Pervious Concrete Pavements. Matéria (Rio J) [Internet]. 2021;26(4):e13078.
[21] Wang, C. (2023). Mechanical performance study and application of pervious concrete with recycled aggregate. Sichuan Building Materials, 43(02), 303-305.
[22] Zhao, J., Wang, Y. Y., Sun, H. B. (2022). Effect of epoxy resin on mechanical and permeability properties of pervious concrete. Functional Materials, 53(09), 9080-9084.
[23] Chen, S. K., Lu, P., Li, B. L., et al. (2022). Influence and evaluation of different fibers on properties of pervious concrete with recycled aggregate. Journal of Applied Basic Engineering Sciences, 30(01), 208-218.
[24] Xin, Z. P., Zhu, Y. G., Xu, P. Z., et al. (2023). Effect of fly ash and polypropylene fiber on properties of recycled pervious concrete. Concrete, (01), 73-77+81.
[25] Qiao, H. X., Su, R., Li, Q., et al. (2023). Study on durability properties of recycled aggregate pervious concrete under different freeze-thaw media based on Weibull distribution. Functional Materials, 54(03), 3134-3142.
[26] Koh Heng Boon, David Yeoh, Norwati Jamaluddin Properties of Pervious Concrete Containing Scrap Tyre Tubes, MATEC Web of Conferences 103, 01015 (2017)
[27] [27] Yan, C., Hu, J. R., & Xie, L. (2023). Preparation and performance testing of modified waste rubber pervious concrete. Bonding, 50(02), 13-17.
[28] Kanghao Tan, Yinghong Qin, Junsong Wang, Evaluation of the properties and carbon sequestration potential of biochar-modified pervious concrete, Construction and Building Materials, Volume 314, Part A,2022,125648,ISSN 0950-0618
[29] Peyman Mehrabi, Mahdi Shariati, Kamyar Kabirifar, Majid Jarrah, Haleh Rasekh, Nguyen Thoi Trung, Ali Shariati, Soheil Jahandari. (2021). Effect of pumice powder and nano-clay on the strength and permeability of fiber-reinforced pervious concrete incorporating recycled concrete aggregate, Construction and Building Materials, Volume 287, 2021, 122652, ISSN 0950-0618
[30] Zhang, Y., Zheng, Y., & Huang, J. D. (2022). Optimization of mechanical properties and influencing factors of pervious concrete. Concrete and Cement Products, (12), 97-100.

[31] Ali Toghroli, Peyman Mehrabi, Mahdi Shariati, Nguyen Thoi Trung, Soheil Jahandari, Haleh Rasekh. (2020). Evaluating the use of recycled concrete aggregate and pozzolanic additives in fiber-reinforced pervious concrete with industrial and recycled fibers, Construction and Building Materials, Volume 252, 2020, 118997, ISSN 0950-0618.
[32] Zhang, Y., & Lv, B. (2022). Application and construction technology of pervious concrete in sponge cities. China Residential Facilities, (05), 127-129.
[33] Zhou, H. L., & Liu, Y. S. (2020). Application of pervious concrete in road drainage design. Journal of Heihe University, 11(03), 182-183+188.
[34] Jiang, Z. W., Sun, Z. P., & Wang, P. M. (2005). Influence of several factors on the performance of porous pervious concrete. Journal of Building Materials, (05), 513-519.
[35] Chen, J. (2022). Application of pervious concrete in bridge drainage design. Transport Manager World, (09), 110-112.
[36] Deng, L. N. (2020). Application of pervious concrete in landscape construction. Modern Horticulture, 43(24), 191-192.
[37] Bao, X., Liao, W., Dong, Z., Wang, S., & Tang, W. (2017). Development of vegetation-pervious concrete in grid beam system for soil slope protection. Materials, 10(96).
[38] Junsong Wang, Qinglin Meng, Ya Zou, Qianlong Qi, Kanghao Tan, Mat Santamouris, Bao-Jie He. (2022). Performance synergism of pervious pavement on stormwater management and urban heat island mitigation: A review of its benefits, key parameters, and co-benefits approach. Water Research, Volume 221, 2022, 118755, ISSN 0043-1354.
[39] Ran, M. Q., Feng, W. B., & Wang, C. Z. (2022). Application of pervious concrete in sponge city construction. Building Technology Development, 49(16), 143-145.
[40] Shabalala, A., & Ekolu, S. (2019). Quality of water recovered by treating acid mine drainage using pervious concrete adsorbent. Water SA, 45(4 October).