Academic Journal of Engineering and Technology Science
ISSN 2616-5767 Vol.7, Issue 6: 169-176, DOI: 10.25236/AJETS.2024.070624

Waterproofing and anti-cracking construction technology of underground engineering based on high-performance self-compacting concrete

Rui Guo[1], Jiaqi Luo[1], Tongqiang Luo[2]

[1]*Jilin Jianzhu University, Changchun, Jilin, 130119, China*
[2]*BYD Auto Industry Company Ltd., Shenzhen, Guangdong, 516200, China*
guor@jlu.edu.cn

Abstract: *As a new type of construction material, high performance self-compacting concrete can effectively improve the compactness and impermeability of the building after pouring. In order to optimize the effect of waterproofing and anti-cracking construction of underground engineering, the waterproofing and anti-cracking construction technology of underground engineering based on high performance self-compacting concrete is proposed. A construction project in the north, focusing on the basement wall, adopts a combination of external defense and internal paste methods for waterproofing and anti-cracking construction. Mechanical excavation is carried out to a predetermined distance above the design base elevation, followed by base repair, laying of the bedding template, pouring of the concrete bedding, and subsequent maintenance. The location and thickness of the masonry are determined, the reinforcing steel grid is arranged and fixed, and then mortar is filled to form a waterproof and anti-crack layer. The wall surface is thoroughly cleaned at the grassroots level, and an additional waterproofing membrane layer is applied for paving construction. Finally, through the design of monitoring points, the humidity and conductivity of different areas are monitored. The results show that the humidity value of the monitoring points is maintained between 36% and 44%, and the conductivity is between 32.9μS/cm and 52.3μS/cm, which proves that the waterproofing layer after construction can effectively prevent the penetration of water.*

Keywords: *concrete; underground construction; waterproofing and anti-cracking; construction technology*

1. Introduction

As an important infrastructure for urban development, underground works are increasingly being constructed, covering a wide range of fields such as basements of high-rise buildings, underground parking lots, subway tunnels, and comprehensive pipeline corridors. While carrying urban functions, these underground projects also face complex and changing groundwater environment and stringent durability requirements. Therefore, how to effectively solve the waterproofing and anti-cracking problems of underground projects has become the key to protect the quality of the project and extend its service life[1]. In recent years, high-performance self-compacting concrete, by virtue of its excellent fluidity, filling and durability, has shown great potential for application in waterproofing and anti-cracking construction of underground projects, and has become a hotspot of attention in the academic and engineering circles. Due to the fact that underground engineering is below the water table for a long time, it is affected by various factors such as groundwater pressure, soil pressure, chemical erosion, etc., and is very prone to quality problems such as water seepage and cracks, which seriously affects the safety of the structure and the use of the function. Traditional waterproofing construction methods, such as setting waterproofing roll-roofing, applying waterproof coating, etc., although can play a waterproof role to a certain extent, but there are problems such as high construction difficulty, difficult to guarantee quality and high maintenance cost[2]. Therefore, it is particularly important to explore new, efficient and reliable waterproofing and anti-cracking construction techniques. As a new type of construction material, high-performance self-compacting concrete, through the optimization of the mix ratio design, the concrete can be automatically compacted without vibration during the pouring process, which reduces the production of construction joints and air bubbles, significantly improves the compactness and impermeability of the concrete, and provides a new solution for the waterproofing and anti-cracking construction of underground projects. In recent years, scholars at home and abroad

ISSN 2616-5767 Vol.7, Issue 6: 169-176, DOI: 10.25236/AJETS.2024.070624

have made significant progress in the research of high-performance self-compacting concrete[3]. On the one hand, by optimizing the design of mixing ratio and adding additives, the fluidity, filling and durability of self-compacting concrete have been significantly improved; on the other hand, a large number of researches have been carried out on the waterproofing and anti-cracking mechanism of self-compacting concrete, construction process and engineering applications. For example, it is found that the waterproofing performance of concrete can be significantly improved by incorporating appropriate amount of organic or inorganic waterproofing agents; the use of deep penetration crystallization sealing and compacting technology can effectively enhance the compactness and durability of concrete; in addition, the successful application of self-compacting concrete in subway tunnels, comprehensive tube corridors and other underground projects has also provided strong support for its promotion in a wider range of fields[4]. This study aims to solve the waterproofing and crack-resistant problems faced by underground projects in the process of construction and use by deeply exploring the waterproofing and crack-resistant construction technology of underground projects based on high-performance self-compacting concrete.

2. Project overview

The selected underground project is an underground construction project in the north, the red line of the building range of the north side of 61.720m, the south side of 59.713m, the west side of 47.55m, the north, south and west side of the mutual perpendicularity of the red line on the east side of a slanting section of the slope length of 48.022m. The house is facing the north and south[5]. The project is reinforced concrete shear wall structure, twenty-eight floors above ground and one floor underground, with a building height of 84.760m, and a total building area of 25585.18m^2 (of which 23702.74m^2 above ground and 1882.44m^2 underground). The first floor is a car garage and six levels of human defense, and the ground floor is a residential apartment building. The seismic defense classification of the building belongs to Class C building, and the intensity of seismic defense is eight degrees[6]. The design service life of the structure is 50 years, the structural safety level is Grade II, the fire resistance level is Grade I, and the foundation design level is Grade A. The site has been completed. The site has been completed with three passes and one leveling. After the construction team enters the site, effective and reasonable arrangement is made for the construction site; in addition, due to the narrow site, the excavation of the foundation pit adopts the method of nearly straight-wall excavation plus layer-by-layer construction of soil nail wall support, and good drainage is made in the periphery of the foundation pit, the inside of the support, and inside the foundation pit[7].

When the project is planned to be constructed in sections below ±0.000, protective railings are erected along the periphery of the foundation pit with steel pipes, with a height of 1.2m; the outer perimeter wall is built with a 2.5m perimeter wall according to the boundaries specified by the construction unit, and a large gate is opened in the north-west corner of the site; an entrance door to the production area is set up in the north-east corner. The site is also proposed to build a janitor's house, an office, a steel processing shed, a carpentry shed, a power distribution room and a living area, etc., in order to meet the requirements of civilized construction.

The soil layers of the building site within the influence of the pit works are categorized into three engineering geological layers with specific soil parameters as shown in the table 1 below.

Table1: Building site soil parameters

ground level		elevation	Thickness
1	Fill	-0.2~-5.6m	0.5-3.4m
2-1	Pulverized soil	-2.5~-6.7m	0.5-.2m
2-2	Powdered sand	-3.0~-11.0m	2.9-8.0m
3-1	Fine sand	-5.6m~20.9m	10.2-15.1m
3-2	Pulverized soil	-15.9m~-22.8m	1.3-7.7m
3-4	Fine sand	-17.2m~23.2m	0.8-0.6m
-35	Pulverized soil	-18.0m~-30.6m	0.21-10.0m

The foundation pit is mainly in the layer of silt sand soil, which has poor stability and bearing capacity. Sandy soil has poor cohesion, large inter-particle pores, good permeability, low cohesion, large internal friction angle, and high permeability coefficient of the soil layer, which is prone to erosion by flowing water.

Groundwater in the exploration depth of the site where this project is located is loose rock-like pore diving and pressurized water. There is a river distribution in the northwest corner of the site, and the foundation pit is affected to a certain extent, so it is necessary to take measures to reduce the impact on the foundation pit[8]. Through geological exploration, pore water is mainly stored in three layers of shallow sandy soil, and the form of recharge is mainly atmospheric precipitation, surrounding surface water and lateral groundwater infiltration, and the mode of discharge is mainly evaporation and lateral discharge, and the depth of the groundwater level during the exploration period is 0.6-4.2m, and the depth of the stabilized groundwater level is 0.7-4.0m, and the west side of the foundation pit is close to the ditch, and the groundwater level of this section is affected by the surface water. Obviously. According to the hydrogeological data of the region, the annual variation of pore diving is generally around 3.00m. The pore pressure water is mainly stored in the deep sandy soil, receiving lateral recharge, with lateral runoff as the main source, and the water richness is good. According to the regional hydrogeological data, the pore bearing pressure water has no influence on the excavation of the foundation pit of this project due to the thick soil of the overlying relatively waterproof top plate[9].

3. Construction process

3.1 Trench clearing and concrete bedding construction

Due to the excavation pit elevation being 6-10cm higher than the designed base elevation, the pit must be leveled again. The leveling method involves manual digging, manual repair, and mechanical tamping. During the repair process, it takes continuous measurements to control the base elevation. While shoveling, it sets up markers every 2-3m² to guide workers in their shoveling and repair work. The requirements are to achieve a smooth and undisturbed base earth surface, strictly adhering to the quality requirements of earthwork construction[10]. The work is carried out in strict accordance with the quality requirements of earthwork. Immediately after the completion of excavation, the foundation repair work was carried out. Workers holding shovels, scrapers and other tools, according to the instructions of the stakes, the substrate is carefully repaired to ensure that the surface is flat and without bumps. Subsequently, small machines or manual tamping methods are used to compact the repaired substrate and improve the bearing capacity of the foundation[11]. In the process of repairing and tamping, special personnel are arranged to carry out follow-up measurements, and the elevation of the foundation is checked regularly by using a level meter to ensure that it meets the design requirements. At the same time, quality supervision is strengthened to ensure that the surface of the subsoil is smooth, undisturbed and meets the quality standards of earthworks.

Any surface debris is thoroughly removed and ash bedding is carried out to the designated elevation of -7.65m to ensure proper compaction and leveling. During the pouring of the concrete bedding, the gray cake control measures are implemented to effectively manage the bedding elevation. It is imperative to maintain the vertical and horizontal spacing of the gray cake within a limit of 1.8 meters. Then a 100mm thick C15 fine gravel concrete bedding is poured to ensure that the elevation of the top surface is accurately controlled at -7.55m.[12].

High-quality C15 fine stone commercial concrete was selected and delivered directly to the construction site through pipelines to reduce the risk of segregation during transportation. When pouring, the sequence from east to west was followed to ensure that the concrete flowed evenly and naturally filled all corners, showing the unique fluidity and filling capacity of self-compacting concrete. Insertion vibrators were used for vibration to ensure that there were no voids and bubbles in the concrete to achieve the design requirements for compactness[13]. At the same time, with the vibration, the concrete surface is smoothed and calendared in a timely manner, in two stages, to ensure the flatness and aesthetics of the mat surface. Immediately after the completion of pouring, cover the surface of the bedding layer with sacks or plastic film to reduce water evaporation, followed by regular watering and curing to ensure that the concrete hardens under appropriate temperature and humidity conditions. The curing period lasts at least until the concrete strength reaches 1.2 MPa, which is necessary for subsequent foundation construction. During this period, it is also necessary to carry out regular inspections of the bedding layer to ensure that there are no cracks, no spalling and other quality problems, in order to lay a solid foundation for the smooth progress of the subsequent processes.

3.2 Brick tire membrane masonry, stucco construction

Except for the north side of N-axis where scaffolding can be erected to support the mold for the construction of external anti-external sticker method, the other three sides of the project adopt the external anti-internal sticker method, which requires the construction of brick molds. Except for the

ISSN 2616-5767 Vol.7, Issue 6: 169-176, DOI: 10.25236/AJETS.2024.070624

east side of the 34 axis, the brick tire membrane is built to the same level with the original natural ground in order to bury the drainage and as the foundation of the north-south pedestrian passageway, and the rest of the south and west sides are built until the construction space is enough for the external defense and external posting method[14]. Taking into account the template system at least 246mm wide, the work surface of the workers by 350mm wide, that is, the construction space should be at least 600mm above (above the top of the brick mold, workers can stand on the top of the brick mold or the top of the brick mold to set up a single row of scaffolding, and then the basement wall using the outside of the outside of the anti-adhesion method of waterproofing roll-roofing).

The brick wall is close to the soil nail wall, and the thickness of the brick wall changes with the slope of the soil nail wall. Along the height of the wall, nΦ8 wall horizontal through-length compression bar is installed every 1.5m. The value of n is calculated according to the pressure of a through-length Φ8 rebar by every 120mm thick wall, and no less than 2. At the same time, it is necessary to ensure that the horizontal gray joint is at least 2mm mortar layer thickness above and below the horizontal longitudinal reinforcement. The soil nail is welded on the wall tie bars, and the distance between the soil nail and the wall tie bar is 1.5m. The wall tie bar and each through-length bar in the wall should be firmly tied at the cross position, extending to the last through-length bar in the wall as the bending anchor, and the welding length is 1,000mm from the position of the soil nail wall and wall tie bar. In areas where the construction space is less than 120mm, support is directly carried out on the original soil-nailed wall, and a 20mm thick waterproof protective layer is then plastered with 1:3 cement mortar. The brick tire membrane structure is shown in the Figure 1 below.

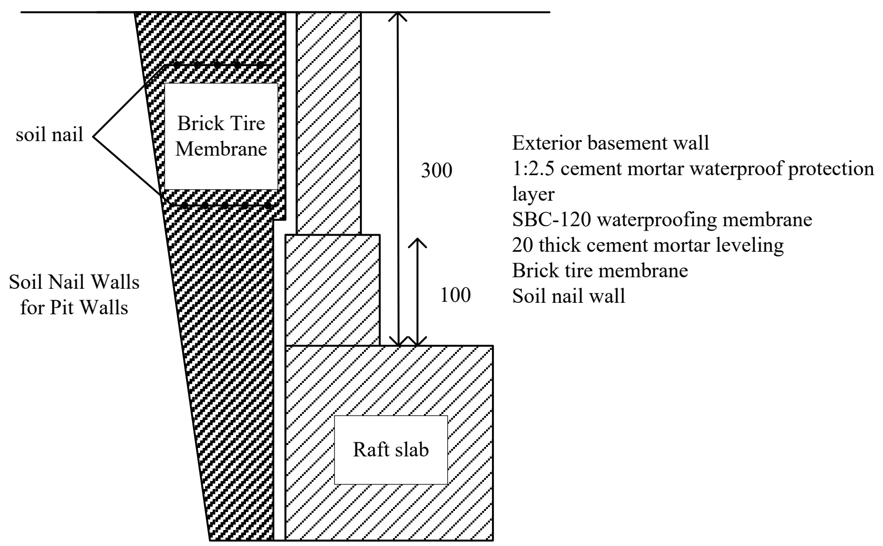

Figure1: Brick Tire Membrane Structure

3.3 Construction of waterproof anti-cracking layer

Waterproofing membrane using polyethylene polypropylene composite waterproofing roll-roofing (SBC-120), there must be a factory quality certificate and the corresponding qualification level testing department issued by the performance test report and instructions for use, after entering the field should be carried out specifications and appearance check. Appearance check mainly check the coil in the crease, impurities, glue blocks, dents, the number of joints per coil and other aspects of qualified, qualified sample retesting in accordance with the provisions, and the implementation of witness sampling and inspection, retesting waterproofing roll-roofing tensile strength at break, elongation at break, low-temperature bending, impermeability and other properties, qualified before being used in construction.

The adhesive is made of polypropylene bonding adhesive powder plus ordinary silicate cement, which is prepared according to the weight ratio of adhesive powder: cement: water = 1:20:60. When mixing, first combine the dry materials, including adhesive powder and a portion of the cement, and then add water and mix thoroughly before incorporating the remainder of the cement.

With a volume ratio of 1:3 cement mortar in the pad layer on the leveling layer construction, should be flat, solid, clean, no bumpy shape and sharp particles, the thickness of 20mm, cement strength grade is not less than 32.5. its flatness requirements are: 2m long ruler and wedge-shaped plug ruler to check the surface of the leveling layer and the maximum gap between the test ruler should not exceed 5mm. membrane waterproofing construction should be inspected before the grassroots level, the yin and yang corners should be made into rounded corners. Yin and Yang corners should be made into rounded corners, arc radius should not be less than 50mm. the surface should be free of loose, sanding, skinning, cracking, loosening, bulging, peeling, no water and other phenomena.

The pile reinforcement is well calibrated and the surface of the pile head is cleaned up. Firstly, the pile head is waterproofed by applying an 8 to 12 millimeter thick layer of polymer cement waterproofing mortar. The layer should extend around the pile head and within a 15-centimeter radius of the pile root. It should be ensured that the overlap between the pile head's side and the flat waterproofing membrane is measured to be at least 10 centimeters. The waterproof mortar is evenly coated with two consistent coats by using a brush, and one hour is left to dry between the coats. The first coat is ready for the second when it no longer leaves marks upon finger pressing. If the first coat becomes excessively dry, it should be lightly sprayed with water to rejuvenate it prior to applying the second coat. The polymer cement waterproofing mortar must be applied within 30 minutes of mixing. Once the waterproofing process is completed, the waterproofing should be maintained by sprinkling water for 48 hours. Additionally, an extra waterproofing membrane should be installed at the pile head, the yin and yang corners, as well as the perimeter of the raft slab. For the yin and yang corners, this extra layer should extend 25 centimeters upwards, downwards, to the right, and to the left. Note that, although the construction is completed, acceptance of the concealed work can only proceed after the subsequent process. The waterproofing membrane used is 2.3mm thick SBC-120, and the paving method employs cold bonding technology. The paving process is begun by determining the precise installation location. First, the facade is paved, and then the plane is paved. The plane paving starts from the top of the brick mold and proceeds longitudinally from top to bottom. This paving should then extend to the other planes, with the upper and lower coil planes laid in an east-west direction. It is crucial that the paving directions are not perpendicular to each other. Adjacent coil joints should be staggered by more than 50cm or 1/3 of the coil width, and the overlap width for both short and long edges should be at least 10cm. During paving, cement adhesive is evenly applied on the surface of the base layer (leveling layer) and the corresponding coil surface by using a brush, ensuring a consistent thickness of approximately 1mm. There should be no brushing leakage or white spots, and slight overspray is acceptable but not underspray. When the coil is laid on the opposite side, adhesive is applied to one of its surfaces by using a brush approximately 50cm in length and 10cm wider than the coil's width. Once the adhesive is applied, the coil is positioned downwards and pressed firmly by using a spatula to compact and remove any excess adhesive, ensuring a secure bond. The waterproofing layer of the coil should be tightly bonded and sealed, free from wrinkles, edges, bubbles, or other defects. The allowable deviation for the coil's overlap width is -10mm. There should be no bumps on the corner elevations or planes. Coil joints should be positioned in a plane, starting from an elevation of at least 60cm. At intersections, cross-lapping should be used to stagger the joints. After construction is completed, implement maintenance and management measures to prevent surface damage. The waterproofing membrane and linoleum protection at the top of the brick wall will be covered with a single layer of brick protection using white mortar, allowing for a 30cm joint size for subsequent construction and ensuring adequate coverage and protection.

Coil waterproofing layer is completed and acceptance should be done in a timely manner after the protective layer. Protective layer should comply with the following provisions: facade waterproofing protective layer using 20mm thick 1:2.5 cement mortar plaster as a protective layer, plane waterproofing protective layer using C25 fine stone concrete construction method, thickness of 50mm. Protective layer must be smooth and clean, there should be no peeling, sanding and other phenomena, the protective layer construction must be in the waterproofing layer quality acceptance before entering the construction of protective layer, The top surface elevation should be -7.5m.

4. Construction Effect Analysis

4.1 Design of waterproofing monitoring locations

In order to comprehensively assess the effectiveness of waterproofing and anti-cracking construction technology of underground engineering based on high-performance self-compacting concrete, it is necessary to reasonably set up monitoring points after the completion of the construction, in order to collect key data for analysis. In this regard, a total of three construction areas in this paper are designed for monitoring points, respectively, for underground engineering corners, pipelines

ISSN 2616-5767 Vol.7, Issue 6: 169-176, DOI: 10.25236/AJETS.2024.070624

through the wall and construction joints and pouring zones, the specific monitoring points are laid out as follows.

At each corner of the underground works, two monitoring points were set up along the inner and outer sides, forming a diagonal layout to fully assess the integrity of the waterproof layer at the corner. The spacing between the points is 1.5 meters to ensure that the monitoring scope covers the entire waterproof layer in the corner area. Embedded humidity sensors were used and installed about 5mm below the waterproof layer to avoid data bias caused by direct exposure to air. For each pipe through the wall, three monitoring points are set around the pipe perimeter, located above, below and to the side of the pipe, with a spacing of 0.8 meters. Monitoring was carried out using a high-precision conductivity meter to assess whether the waterproofing layer was effective in preventing water penetration by measuring changes in electrolyte concentration near the contact surface between the waterproofing layer and the pipe. Construction joints and backing zones are weak links in waterproofing and require special attention. Three monitoring points are set up on each side of each construction joint or backwatering zone, with a spacing of 1 meter to ensure coverage of the entire joint area. A waterproof membrane that features an integrated conductivity sensor, which is strategically positioned near the surface of the waterproof layer, is incorporated to facilitate real-time monitoring of water infiltration specifically at the joints.

4.2 Analysis of monitoring results

The results of humidity as well as conductivity monitoring in different monitoring areas are shown in the table below.

Table2: Waterproofing layer humidity and conductivity monitoring results

Monitoring Area	Monitoring Point ID	Humidity (%)	Conductivity (μS/cm)	Remarks
Corner - Inner Side	1-A	42.5	47.3	Initial monitoring data
Corner - Inner Side	1-B	41.8	46.5	Initial monitoring data
Corner - Outer Side	1-C	43.2	48.1	Initial monitoring data
Pipe Penetration - Top	2-A	36.7	32.9	Dry condition, initial data
Pipe Penetration - Bottom	2-B	37.5	34.1	Slightly damp, initial data
Pipe Penetration - Side	2-C	36.2	33.2	Dry condition, initial data
Construction Joint - Left	3-A	40.5	42.8	Initial monitoring data
Construction Joint - Mid	3-B	39.9	41.9	Initial monitoring data
Construction Joint - Right	3-C	39.2	41.1	Initial monitoring data
Post-pour Strip - Start	4-A	44.8	52.3	Slightly moist, initial data
Post-pour Strip - Mid	4-B	44.2	51.1	Slightly moist, initial data
Post-pour Strip - End	4-C	43.6	50.5	Initial monitoring data

As can be seen from the table 2, the moisture values at all monitored locations, whether at corners (e.g., 1-A, 1-B, 1-C), pipe penetrations (e.g., 2-A, 2-B, 2-C), or construction joints and back-up zones (e.g., 3-A, 3-B, 3-C, 4-A, 4-B, 4-C), remained relatively low (mostly between 36 and 44 percent), and were well below the values that could trigger a thresholds for water seepage or moisture problems. This indicates that the construction method proposed in this paper effectively prevented moisture infiltration in these critical areas and demonstrated efficient waterproofing performance. At the same time, the monitoring data showed good consistency and uniformity among the points, indicating that the waterproofing layer was constructed with uniform quality throughout the underground works, and there were no obvious local weak points. For example, at the pipe penetration wall, both humidity values and conductivity remained similar at both the top (2-A), bottom (2-B) and side (2-C), indicating that the waterproofing treatment was effectively implemented both vertically and horizontally. Conductivity, as a measure of a material's ability to conduct electricity, also indirectly reflects the waterproofing layer's capacity to insulate against moisture. The conductivity at all monitoring points was at a low level (mostly between 32.9 μS/cm and 52.3 μS/cm), indicating that the waterproofing layer not only prevented the penetration of water, but also effectively isolated the electric current that might be conducted through the water, which enhanced the structural safety of the underground works.

5. Conclusion

This study centers on the waterproofing and anti-cracking construction technology of underground engineering based on high-performance self-compacting concrete, which not only theoretically analyzes the unique advantages of high-performance self-compacting concrete in enhancing the waterproofing and anti-cracking performance of underground engineering, but also verifies its feasibility and validity through actual engineering cases. This study not only enriches the theoretical system of waterproofing and anti-cracking construction technology for underground engineering, but also provides scientific guidance and technical support for actual engineering construction, which is of far-reaching significance.

Acknowledgement

Fund project: Ministry of Education's Collaborative Education Project on Industry and Education: Innovation in Civil Engineering Teacher Training in the New Engineering Concept (Project Number: 231107061071647)

References

[1] Sadeghiravesh M H , Khosravi H , Abolhasani A .Selecting proper sites for underground dam construction using Multi-Attribute Utility Theory in arid and semi-arid regions[J].Journal of Mountain Science, 2023, 20(1):197-208.

[2] V. Trushko O , Trushko V L , Demenkov P A .Construction of Underground and Multi-story Car Parks in High-density Urban Areas[J].International Journal of Engineering (IJE), 2024, 37(2): 224-236.

[3] Lane-Nott P. Is a new approach to underground construction about to transform the engineering landscape?[J]. Highway Engineering Australia, 2023, 54(6): 38-40.

[4] Feng J , Zhang W , Wu Z .An innovative measurement-while-drilling method applied in construction of underground stress relief hole with more vibration events[J].Arabian Journal of Geosciences, 2022, 15(6):1-11.

[5] Ryu J S , Park D H , Jang Y G .Three-dimensional Underground Facility Automatic Renewal System Construction to Updated Integrated Underground Spatial Map[J].Sensors and materials: an International Journal on Sensor Technology, 2023, 35(9 Pt.3):3313-3324.

[6] Ren J , Zhang K , Xu X S ,et al. Performance evolution of self-compacting concrete for ballastless track based on high-cycle fatigue damage constitutive model[J].Journal of Central South University, 2023, 30:2048 - 2063

[7] Chun-Tan F , Qing-Guo L , Jian-Ping Y ,et al. Study on Fine Classification of Surrounding Rock During Construction Stage of Underground Cavern with Layered Rock Mass[J].China Journal of Highway and Transportation, 2023, 36(4):169-182.

[8] Ostrowski K, Furtak K .Influence of Carbon Fibre Reinforced Polymer and Recycled Carbon Fibres on the compressive behaviour of self-compacting high -performance fibre-reinforced concrete[J]. Archives of civil engineering, 2023, 69(2):53-64.

[9] Zhao H , Sun W , Wu X ,et al. Sustainable self-compacting concrete containing high-amount industrial by-product fly ash as supplementary cementitious materials[J].Environmental science and pollution research international, 2022, 29(3):3616-3628.

[10] Qin D , Zong Z , Dong C ,et al. Long-term behavior of sustainable self-compacting concrete with high volume of recycled concrete aggregates and industrial by-products[J].Structural Concrete, 2022, 24:3385 - 3404.

[11] Kumar S , Kapoor K , Singh S P .Application of silica fume in high-volume fly ash self-compacting recycled aggregate concrete[J].Australian journal of civil engineering, 2023, 21(2):207-223.

[12] Wang J , Yang Y , Yap M P S .Recent developments in utilization of nano silica in self-compacting concrete: A review[J].Structural concrete: Journal of the FIB, 2023, 24(6):7524-7548.

[13] Kumar S , Gupta P K , Iqbal M A .Parametric Sensitivity Analysis of High-Strength

ISSN 2616-5767 Vol.7, Issue 6: 169-176, DOI: 10.25236/AJETS.2024.070624

Self-compacting Alkali-Activated Slag Concrete for Enhanced Microstructural and Mechanical Performance [J].Iranian Journal of Science and Technology, Transactions of Civil Engineering, 2024, 48(3): 1353- 1371.
[14]Properties of ultra-high-performance self-compacting fiber-reinforced concrete modified with nanomaterials[J].Nanotechnology Reviews, 2023, 12(1):363-87.
[15] María Eugenia Maciá-Torregrosa, Castillo, Rocío Sancho. Residual Strength and Thermal Conductivity of Self-Compacting Concrete with Recycled Expanded Polystyrene Subjected to High Temperatures[J]. Advanced Materials Research, 2022, 1174:15 - 23.