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Impact of typical environments in China's western mountainous areas on the durability of railway concrete: a review

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Abstract

Purpose – This study aims to analyze the impact mechanism of typical environments in China's western mountainous areas on the durability of railway concrete and propose measures to improve durability.

Design/methodology/approach – With the continuous promotion of infrastructure construction, the focus of China's railway construction has gradually shifted to the western region. The four typical environments of large temperature differences, strong winds and dryness, high cold and low air pressure unique to the western mountainous areas of China have adverse effects on the durability of typical railway structure concrete (bridges, ballastless tracks and tunnels). This study identified the characteristics of four typical environments in the western mountainous areas of China through on-site research. The impact mechanism of the four typical environments on the durability of concrete in different structural parts of railways has been explored through theoretical analysis and experimental research; Finally, a strategy for improving the durability of railway concrete suitable for the western mountainous areas of China was proposed.

Findings – The daily temperature difference in the western mountainous areas of China is more than twice that of the plain region, which will lead to significant temperature deformation and stress in the multi-layered structure of railway ballastless tracks. It will result in cracking. The wind speed in the western plateau region is about 2.5 to 3 times that of the plain region, and the average annual rainfall is only 1/5 of that in the plain region. The drying effect on the surface of casting concrete will significantly accelerate its cracking process, leading to serious durability problems. The environmental temperature in the western mountainous areas of China is generally low, and there are more freeze-thaw cycles, which will increase the risk of freeze-thaw damage to railway concrete. The environmental air pressure in the western plateau region is only 60% of that in the plain region. The moisture inside the concrete is more likely to diffuse into the surrounding environment under the pressure difference, resulting in greater water loss and shrinkage deformation of the concrete in the plateau region. The above four issues will collectively lead to the rapid deterioration of concrete durability in the western plateau region. The corresponding durability improvement suggestions from theoretical research, new technology development and standard system was proposed in this paper.

Originality/value – The research can provide the mechanism of durability degradation of railway concrete in the western mountainous areas of China and corresponding improvement strategies.

Keywords Western mountainous areas, Concrete, Durability, Environment

Paper type Research paper

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1. Introduction

With the implementation of “The Belt and Road” strategy, China’s railway construction is gradually moving toward the difficult and dangerous mountains in the west. The Qinghai Tibet Railway is the first plateau railway built in China, which crosses special areas such as Gobi, grasslands, swamps and permafrost by using bridges instead of roads. The successful construction of the Qinghai Tibet Railway indicates that China has the ability to construct railway projects in the western region. However, multiple western railway lines currently under construction or planned will cross the Hengduan Mountains and face more unique and complex climate and geological conditions, posing a more severe test for the durability of railway concrete. The altitude of difficult mountainous areas in western China is generally between 3,000 m and 5,000 m, with high frequency and large amplitude of daily temperature changes. The average wind speed is high, ranging from 2.5 to 3.5 m/s per month, which is about twice that of plain areas. The annual average temperature is relatively low, about −2.0~12.0 ℃. The average altitude is high, and the environmental atmospheric pressure is about 60% of that in plain areas (Bai, 2000, 2001; Yao, 2002; Wu, 2005; Fan, 2008; Ma, 2014). The above environmental conditions make the plateau areas represented by the Qinghai Tibet Plateau have unique environmental characteristics such as large temperature differences, strong winds and dryness, high cold and low pressure.

With the continuous promotion of infrastructure construction in China, especially the planning and construction of railway projects in western mountainous areas, the number of railway lines in plateau areas is gradually increasing. The practice of western railway engineering has shown that concrete structures in the western plateau region are more prone to surface cracking, peeling and other durability problems than those in the plain region. This is mainly related to the accelerating effect of the special environment in the western plateau region on the deterioration of concrete performance (Quan, 2017; Guo, 2018; Ge, 2019; Chen, 2019, 2021; Jin, 2019; Li, 2021; He, 2021). Many scholars have explored related issues, but there is still relatively little systematic research on the durability mechanism of typical railway engineering structures in difficult mountainous areas in the western region. This article will take typical structural concrete of railway engineering as the object and systematically analyze the impact mechanism of four special environments in the western mountainous areas on its durability. Based on this, the methods and suggestions for ensuring the durability of railway concrete in western mountainous areas were also proposed.

2. Influence mechanism of typical environments on the durability of railway concrete structures

2.1 Large temperature difference environment

2.1.1 Environmental characteristics. For railway structural concrete, its surface temperature is mainly determined by two factors: convective heat transfer with the environment and solar radiation. The convective heat transfer with the environment is mainly related to the ambient temperature, while solar radiation is mainly related to the radiation intensity, as shown in Figure 1. The surface temperature of concrete under sunlight should be expressed as follows:

$$T_{surface} = T_0 + \beta(T_{out} - T_0) + \alpha I_z \tag{1}$$

where T_0 is the initial value of concrete surface temperature, ℃; β is the surface heat transfer coefficient of concrete, W/(m^2.℃); T_{out} is the ambient temperature, ℃; α is the solar radiation absorption rate; I_z is the amount of solar radiation, kJ/m^{2}h and C is the specific heat capacity of concrete, kJ/kg ℃.

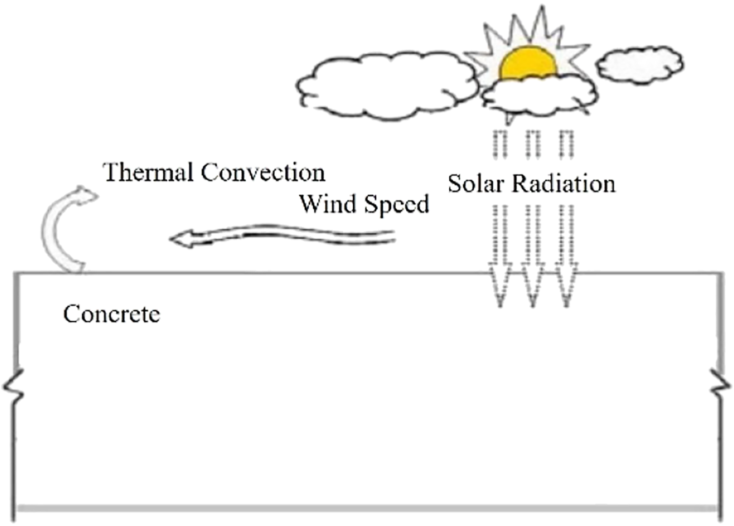


Figure 1. Schematic diagram of concrete surface temperature composition

Source(s): Authors' own work

Tibet is the region with the richest total solar radiation in China. The annual total solar radiation of the whole region is mostly between 6,680 and 8,400 MJ/m^2 y, and the annual sunshine hours range from 3,200–3,300 hours. By comparison, the total annual solar radiation in Sichuan Province ranges from 3,344–4,190 MJ/m^2 y, with an annual sunshine duration of 1,000–1,400 hours. In addition, the environmental temperature changes in the Qinghai Tibet Plateau region are significant. When combined with solar radiation, the daily temperature variation of the surface of structural concrete in this area is significantly higher than that in plain areas. Figure 2 shows the measured monthly average daily temperature

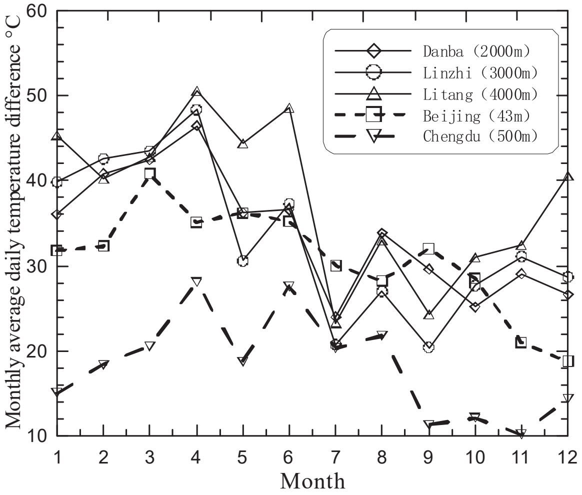


Figure 2. Measured data of monthly average daily temperature difference of typical cities in plateau and plain areas

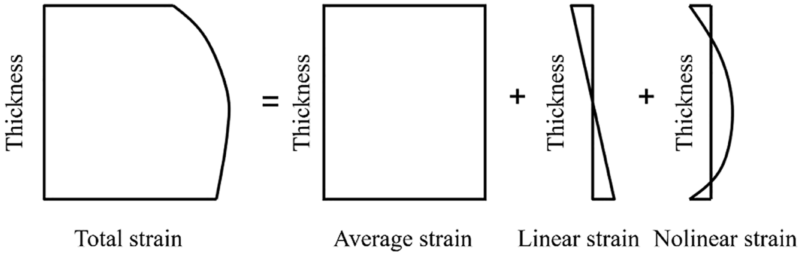
Source(s): Authors' own work

difference data of typical cities in different altitude areas of the Qinghai Tibet Plateau from January to December 2021 and compares it with Beijing and Chengdu in plain areas. According to the data, the monthly average surface temperature difference in typical cities in plateau areas is higher than that in plain areas from January to June and from October to December. The daily temperature difference in plateau areas increases most significantly from April to June, approaching twice that of the Chengdu area. The large temperature difference on the surface of structural concrete caused by the combined effect of environmental heat exchange and sunlight will lead to significant temperature stress on the pier body, bearing platform and track structure of railway engineering bridges, thereby causing durability issues.

2.1.2 Mechanism. The surface temperature of concrete in railway engineering is mainly affected by two factors: convection and solar radiation. The Qinghai Tibet Plateau region experiences significant temperature fluctuations and strong solar radiation, which will result in higher amplitude and frequency of surface temperature changes in structural concrete compared to plain areas. The thermal deformation coefficient of concrete materials is mainly determined by key parameters such as aggregate type, cement-to-aggregate ratio and sand ratio. It is usually within the range of 8.0–12.0 με/°C (Wang, 2018). The frequent changes in surface temperature of concrete will lead to complex temperature deformations inside it. Under the constraint of adjacent structures or self-constraint, nonlinear temperature deformation inside concrete will generate temperature stress. When the temperature stress exceeds the ultimate tensile strength of concrete, it will cause cracking. For railway engineering, ballastless track structure is a core component of high-speed railway infrastructure and has been successfully applied in various high-speed railway lines in China (Zhao, 2006; Lu, 2015). Due to the significant influence of environmental temperature and solar radiation on the ballastless track structure, cracking caused by temperature difference stress is more pronounced.

The ballastless track is a typical multi-layered strip structure that prevents direct transmission of interlayer temperature deformation by isolating the upper and lower layers (Zhao, 2008). However, the frequent changes in environmental temperature in the western plateau region will lead to significant temperature stress inside its single-layer concrete structure. For single-layer slab concrete structures, their temperature deformation can be decomposed into three categories: average strain, linear strain and nonlinear strain, as shown in Figure 3.

The average strain in the slab concrete structure will generate uniformly distributed tensile or compressive stress under the frictional force of the lower track structure. However, due to the length of the Chinese Railway Track System (CRTS) III ballastless track slab in China being 5600 mm, the uniform tensile stress mentioned above usually does not cause tensile cracking of the track slab (Zhao, 2014; Qin, 2020). The linear strain will cause bending deformation of the concrete ballastless track slab structure, and uneven support between



Source(s): Authors' own work

Figure 3. Schematic diagram of internal strain decomposition of slab concrete structure

layers of the track structure will occur (Zhao, 2021), as shown in Figure 4. When there is a large temperature gradient in the track slab, linear temperature deformation will occur inside, leading to warping of the concrete track slab. The support state between the track plate and the lower structure has changed from uniform support to local support. In recent years, multiple operating lines have experienced problems such as poor track smoothness caused by linear temperature deformation, which affects the comfort of train operation (Tian, 2020). More importantly, the local support state has a significant impact on the stress distribution inside the track. In China's track structure design system, the track slab is a thin plate structure placed on an elastic foundation, which presents a surface-supported state under the action of train loads. But due to the linear temperature deformation effect, its actual support state becomes lateral support. At this point, the stress state in the track plate is significantly higher than the verification results of the surface support in the design specifications.

On the other hand, the bending state of the track slab coupled with the train load will result in significant bending stress inside the track slab. Figure 5 is a schematic diagram of the local support state under the coupling effect of linear strain of the track slab and train load. As shown in the figure, when the train load acts on the warped track slab, the support state of the track slab will change from bilateral support to multilateral support. At this point, there will be significant bending stress on the lower track plates of the train. Therefore, under the coupling effect of linear temperature deformation and train load caused by the large temperature difference environment in the western plateau, the bending stress of high-speed railway track structure and the risk of cracking will increase.

The nonlinear strain in track slab structures is usually caused by frequent temperature changes, which will be constrained by the structure itself and generate temperature stress. This stress will be superimposed with the average stress and linear stress, acting together on the structural concrete. Therefore, the total internal stress of the concrete in the slab structure

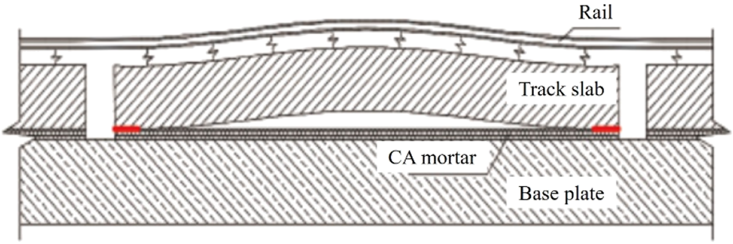


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Figure 4.
Schematic diagram of local support state of track structure under linear strain

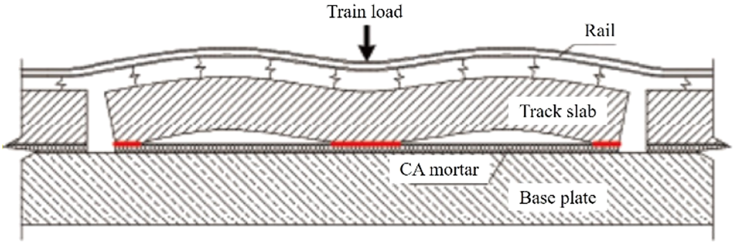

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Figure 5.
Schematic diagram of local support state of track structure under coupling action of linear strain and train load

of railway engineering under a large temperature difference environment is the sum of the stress generated by the average strain, linear strain and nonlinear strain:

$$\sigma_t = \sigma_{axial} + \sigma_{linear} + \sigma_{nonlinear} \tag{2}$$

2.1.3 Durability improvement strategy. The surface temperature of concrete in railway engineering structures mainly comes from convective heat transfer and solar radiation. For casting components such as bridge piers and track bed slabs, insulation and curing techniques can be used in the early stages to prevent the impact of low temperature conditions on early-aged concrete during frequent temperature changes. For long-term casting and prefabricated components such as track slabs, reflective coatings can be applied to the concrete surface to reduce the temperature gradient caused by solar radiation.

2.2 Strong wind and drying environment

2.2.1 Environmental characteristics. Due to factors such as high-altitude atmospheric circulation and solar radiation, the average wind speed in the western mountainous areas of China is significantly higher than that in the plain region. Figure 6 shows a comparison of monthly average wind speeds between a typical city in the plateau region (Shannan) and a typical city in the plain region (Chongqing). The monthly average wind speed in Shannan City can almost reach 2.5–3 times that of Chongqing City in the plain area.

The average annual rainfall in the Qinghai Tibet Plateau region of China is generally lower than that in the plain region. The statistics of the average annual rainfall from 1981 to 2010 are shown in Figure 7. As shown in the figure, the average rainfall distribution on the Qinghai Tibet Plateau generally shows a pattern of more in the east and less in the west, with higher annual average rainfall near the eastern plains, reaching up to 750 mm. The average annual rainfall in the western region of the Qinghai Tibet Plateau is only 150 mm. The combination of less rainfall and environmental wind speed creates a unique windy and drying environment in high-altitude regions, which will accelerate the water loss of concrete surfaces on railway bridge piers, abutments and casting track bed structures, leading to durability problems such as shrinkage and cracking.

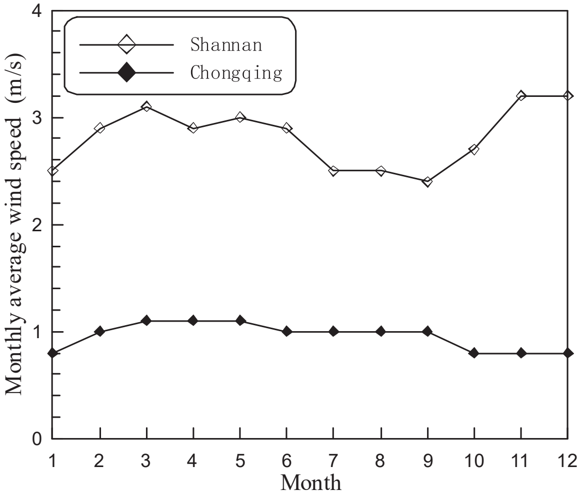

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Figure 6.
The measured monthly average wind speed of typical cities in plateau and plain areas

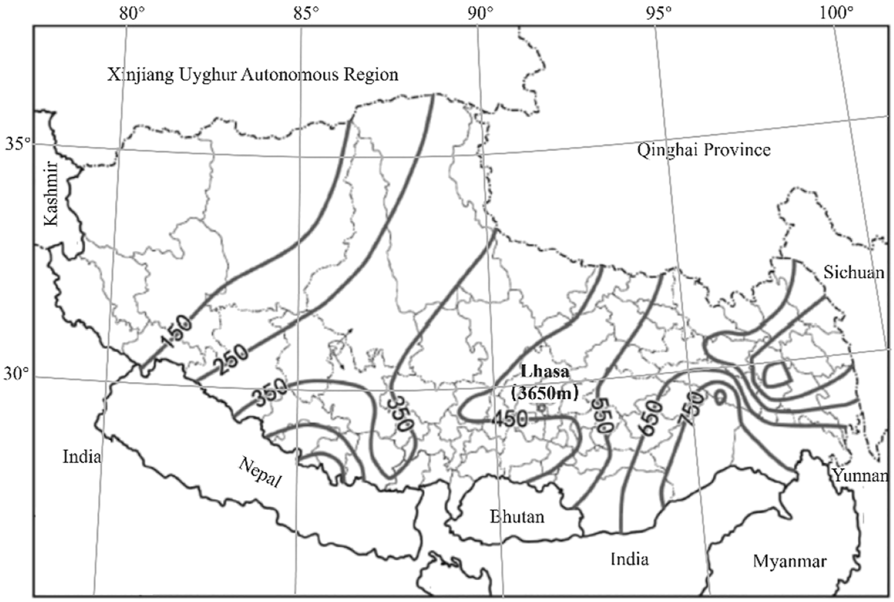

Figure 7. Annual average rainfall of the Qinghai Tibet Plateau from 1981 to 2010 (unit: mm)

Source(s): China Meteorological Data Network

2.2.2 Mechanism.

(1) Surface drying mechanism of concrete under changes in environmental wind speed

After demolding, the concrete structure of railway engineering will immediately undergo moisture exchange with the environment. Due to the low humidity in the western plateau region, some of the moisture on the surface of concrete will be lost to the surrounding environment during this process, resulting in a decrease in the moisture content and humidity of the concrete surface. The change in humidity of concrete is the essential influencing factor of its shrinkage development. As the surface humidity level of concrete gradually decreases, shrinkage deformation gradually develops. When deformation is constrained, shrinkage stress will be generated on the surface of the concrete, and cracking will occur when the stress reaches the ultimate tensile strength (Wang, 2021). The change in environmental wind speed is an important factor affecting the rate of water exchange between the drying surface of concrete and the environment. The environmental wind speed in the Qinghai Tibet Plateau region can usually reach 2.5 to 3 times that of plain areas, which will accelerate the process of water loss on the concrete surface of railway structures, thereby increasing the risk of shrinkage cracking. In engineering practice, newly poured structural concrete such as railway pier bodies, abutments, tunnel lining and tower columns are prone to surface cracking under surface drying. This process will affect not only the surface of concrete but also the inner side of concrete structures. The above process will cause nonlinear shrinkage stress inside the concrete, leading to further development of surface cracks inside the concrete (Wang, 2021). These cracks will provide channels for the surrounding medium to erode into the interior of the concrete, and the corrosive medium will directly invade the interior of the concrete through these cracks, corroding the steel bars and causing damage to the concrete structure.

In order to deeply analyze the influence mechanism of environmental wind speed changes on the surface water loss characteristics of concrete, this paper designed an experimental device, as shown in Figure 8, to quantitatively test the quality loss of C50 concrete for railway bridge piers under drying conditions with environmental wind speeds of 0m/s, 5m/s, 10m/s and 15m/s. The test results are shown in Figure 9.

The water loss in railway bridge pier concrete under different environmental wind speeds shows a two-stage pattern with the development of curing age: linear development stage and nonlinear development stage. In the linear development stage, the water loss of concrete increases linearly, and when it reaches a certain point, the development of water loss shows a nonlinear trend. With the increase of environmental wind speed, the water loss rate of bridge pier concrete in the linear development stage significantly increases. The total water loss

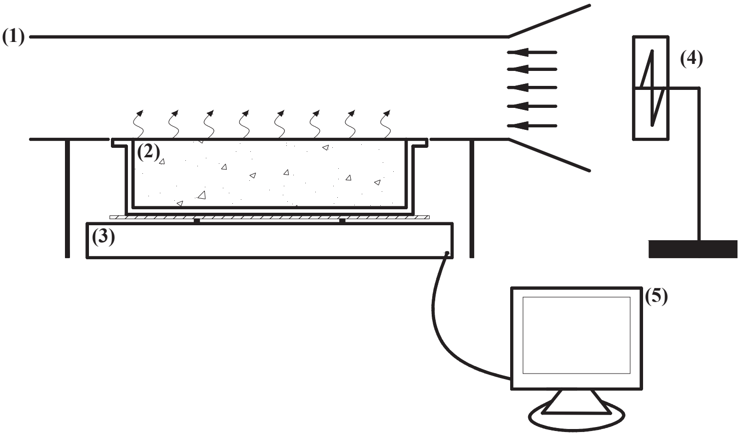

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Figure 8. Test device for water loss characteristics when wind speed changes: (1) induced draft passage; (2) concrete test piece; (3) balance; (4) variable frequency fan and (5) computer

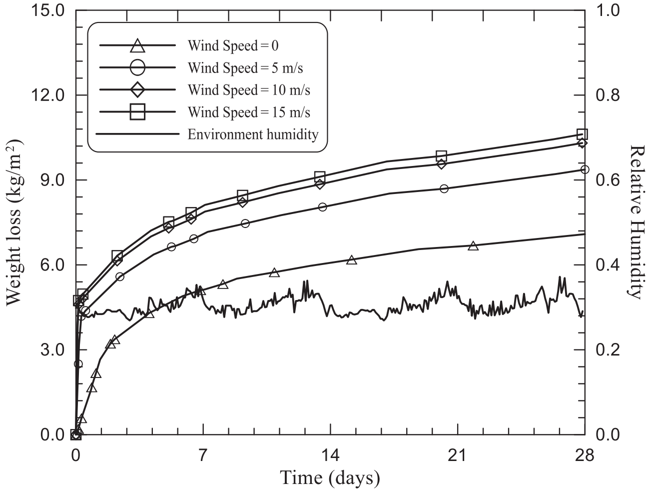

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Figure 9. Test results of concrete water loss under different wind speeds

gradually increases after 28 days. The above pattern is more significant when the environmental wind speed is ≤ 10m/s. When the environmental wind speed reaches 15 m/s, the rate of water loss during the linear stage and the total loss of water over 28 days of concrete change less under the condition of 10 m/s. By analyzing the reasons, it can be concluded that there is a transition layer of relative humidity between the concrete surface and the environment. The moisture inside the concrete diffuses into the surrounding environment through this transition layer. The change in environmental wind speed essentially affects the thickness of the transition layer, which, in turn, affects the migration rate of moisture inside the concrete to the surrounding environment. The transition layer on the surface of concrete under wind speed is shown in Figure 10. As shown in the figure, the drying surface of concrete can be divided into laminar, transition and turbulent zones along the direction of air flow. The transition layer gradually thickens with the increase in flow distance. The thickness of the transition layer is the key factor affecting the water loss rate of the concrete drying surface, which is mainly related to factors such as air flow velocity and ambient temperature on the concrete surface. As the ambient wind speed increases, the transition layer on the concrete surface becomes thinner and the rate of moisture diffusion increases. However, as the ambient wind speed further increases, the transition layer on the drying surface of the concrete almost disappears. The surface humidity level of the concrete is almost the same as the ambient humidity. At this point, the influence of environmental wind speed on the drying effect of concrete surface gradually decreases.

As the ambient wind speed increases within a certain range, the thickness of the transition layer on the drying surface of concrete decreases, leading to increased diffusion rate of moisture and risk of surface shrinkage deformation and cracking. For railway bridge piers, abutments, tower columns and other structural concrete in high-altitude areas, environmental wind speed has a greater impact on durability issues such as surface cracking.

(2) The influence of surface curing on the drying process and durability of concrete

Concrete surface curing is an effective method to reduce surface cracking, but it is not given much attention in practical engineering. In the construction of railway engineering in China, there are still cracking problems caused by untimely and inadequate maintenance. At present, there is relatively little research on scientific maintenance techniques for railway concrete with

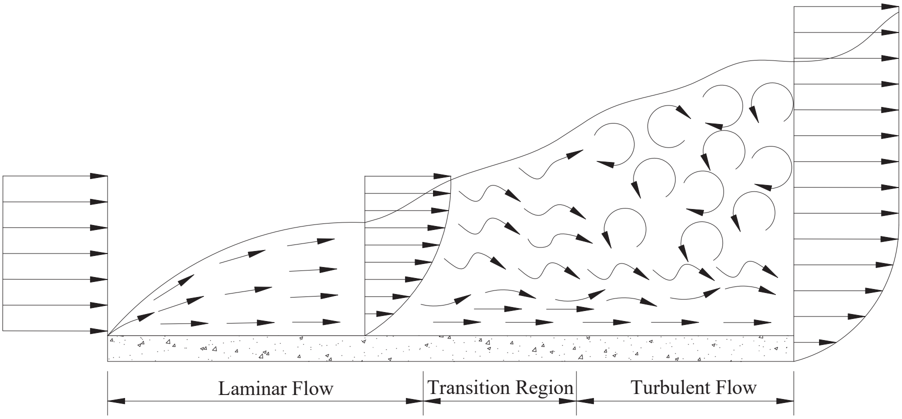

Figure 10. Schematic diagram of concrete drying surface transition layer

Source(s): Authors' own work

different environmental characteristics. There is still insufficient research on the mechanism of surface cracking during the concrete maintenance process. Wang, Xie, Zhong and Li (2022) conducted experimental measurements to assess the changes in water dispersion loss of bridge pier concrete over time under different curing conditions, and the results are shown in Figure 11.

The water loss of concrete specimens with and without film curing still shows a two-stage pattern with the change of curing age. However, the duration of the first stage of concrete water loss is significantly shortened with the extension of curing time. The final cumulative water loss is significantly reduced. The reason is that the first stage of water loss on the surface of concrete under drying conditions corresponds to the humidity saturation period, during which the main loss is free water on the surface of the concrete (Figure 12a). As the curing time prolongs, the free water content on the concrete surface decreases, resulting in a shorter duration of the first stage. On the other hand, the surface curing process also reduces the water loss during the period of humidity reduction on the drying surface of concrete. The reason is that as hydration continues, the water film covering the drying surface of

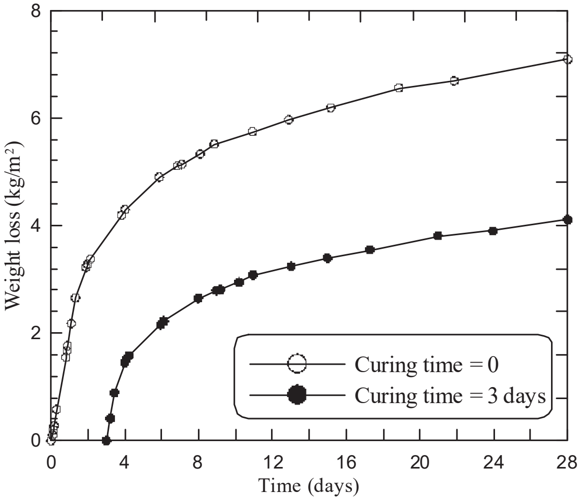

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Figure 11.
Test results of water loss for railway pier concrete under different curing conditions

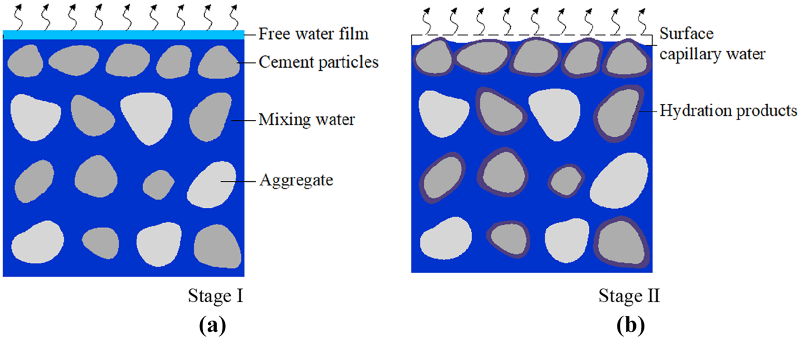

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Figure 12.
Schematic diagram of two stages of concrete surface drying

concrete gradually disappears. The moisture on the drying surface is divided into multiple water islands, with only pore water remaining at the surface capillary pores (Figure 12b). As the surface drying process further develops, curved liquid surfaces appear in the pores of the concrete surface, causing a decrease in surface humidity and the development of shrinkage deformation. For the curing specimens, the cement particles on the concrete surface continuously hydrate during the curing stage, resulting in a reduction in the number and size of surface pores. Therefore, the second stage of water loss rate of the curing specimens is lower than that of the noncuring specimens. The decrease in water loss rate will directly lead to a slowdown in the development of surface shrinkage deformation of concrete, thereby reducing the risk of shrinkage cracking. Therefore, the surface curing process optimizes the pore structure of the concrete surface and reduces the development of shrinkage stress, which is beneficial for improving the durability of railway concrete.

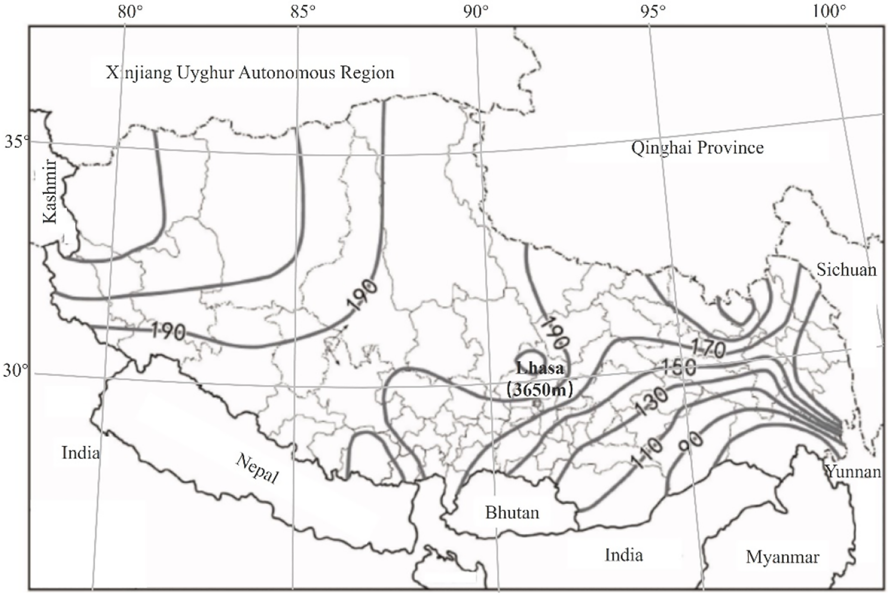
2.2.3 Durability improvement strategy. The strong wind and drying environment mainly affect the process of water loss on the surface of concrete. Therefore, water retention and/or replenishment maintenance measures are effective in reducing surface water loss of concrete. For the concrete body, pre-absorbent medium internal curing technology can be used to supplement the moisture during the concrete drying process, thereby reducing cracking caused by drying shrinkage. For external maintenance, surface coating maintenance or spraying maintenance agents can be used to optimize the structure of the concrete drying surface, reduce surface water loss and thus reduce the risk of shrinkage cracking.

2.3 The cold environment

2.3.1 Environmental characteristics. Since the heat source for environmental temperature is the ground, the higher the distance from the ground, the less ground radiation is obtained. The temperature is correspondingly lower. According to statistics, for every 1,000 m increase in altitude, the temperature will decrease by about 6.0 ℃. The altitude of the Qinghai Tibet Plateau is generally above 3,000 m. Therefore, the environmental temperature in the Qinghai Tibet Plateau region is relatively low and belongs to a high-altitude environment. For concrete, the high cold environment and alternating positive and negative temperatures will have a significant impact on its durability. If the highest temperature is greater than 0 ℃ and the lowest temperature is lower than 0 ℃, it is considered a freeze-thaw cycle day. The contour lines of freeze-thaw cycle days in the Qinghai Tibet Plateau region are shown in Figure 13. From the results in the figure, it can be seen that the annual freeze-thaw cycle frequency in the Qinghai Tibet Plateau region shows a distribution pattern of high in the west and low in the east. The annual freeze-thaw cycle frequency is relatively low near the inland plain area, while it is higher in the western plateau area. The freeze-thaw cycle process will lead to the deterioration of structural concrete in contact with water, such as water piers and tunnel openings in railway engineering, resulting in durability issues.

2.3.2 Mechanism. Freeze-thaw damage mainly occurs in locations such as bridge pier concrete and ballastless track concrete that come into frequent contact with water or snow, particularly in the Qinghai Tibet Plateau. In the northeast region of China, some high-speed railway ballastless track concrete surfaces have shown varying degrees of powdering and peeling. Compared with the Northeast region, the Qinghai Tibet Plateau has a higher frequency of freeze-thaw cycles and larger temperature differences. For example, the annual positive and negative temperature changes alternate up to 190 times in Lhasa, Tibet and other regions. Therefore, railway concrete in the Qinghai Tibet Plateau region will face more severe freeze-thaw cycle damage tests.

Scholars have conducted extensive research on the mechanism of concrete freeze-thaw failure. As early as 1945, Powers proposed the theory of hydrostatic pressure (Powers, 1945). He believes that when the temperature of concrete drops below freezing point, the moisture in

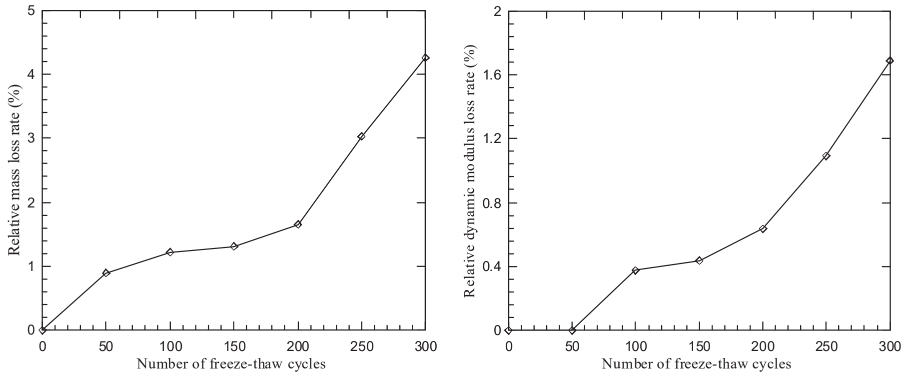


Source(s): China Meteorological Data Network

Figure 13.
Isoline of freezing and thawing cycle days in the Qinghai Tibet Plateau (unit: times)

its internal capillary pores begins to freeze. Due to the volume increase of about 9% between ice and water of the same mass, the water in the capillary pores of concrete will expand when it freezes. At this point, if the unsaturated capillary pores are insufficient to accommodate the volume of ice expansion, static water pressure will be formed on the capillary pore walls. The repeated application of this pressure will cause damage to the capillary walls inside the concrete. This damage will continue to accumulate as the number of freeze-thaw cycles increases. Based on the theory of hydrostatic pressure, Power and Helmuth further proposed the theory of osmotic pressure (Powers, 1953; Jiang, 2020). Due to the presence of pores of different sizes in concrete, the freezing point of water inside varies under the surface tension of the pore liquid. The freezing point of larger pores is close to 0 °C, while the internal freezing point of smaller gel pores is lower. Therefore, water in larger pores freezes first as the ambient temperature decreases. At this point, the concentration of unfrozen solution in the pores continues to increase, while the concentration of solution in smaller pores remains constant. This will create a concentration difference between the large and small pores, and the unfrozen solution in the large pores will migrate toward the small pores. At the same time, the partial pressure of water vapor above the supercooled water in the concrete gel pores is higher than the vapor pressure above the ice interface in the pores at the same temperature, thus forming a pressure gradient in the gel pores and the frozen pores and causing the water in the gel pores to diffuse into the pores containing ice hairs. The above process will generate osmotic pressure inside the concrete.

Liang (2020) tested the frost resistance of C60 railway sleeper concrete and measured the relationship between the concrete mass loss rate and relative dynamic elastic modulus loss rate during freeze-thaw cycles and the number of freeze-thaw cycles, as shown in Figure 14. As shown in the figure, both the mass and dynamic elastic modulus loss significantly increase with the increase of freeze-thaw cycles. The freeze-thaw cycle process is the accumulation of internal damage in concrete, and the number of freeze-thaw cycles is the key factor affecting the various properties of concrete after freezing. The number of freeze-thaw



Mass loss rate
(a)

Relative dynamic modulus loss rate
(b)

Source(s): Liang *et al* (2020)

Figure 14.
Test results of frost resistance of C60 sleeper concrete

cycles in the Qinghai Tibet Plateau region is significantly higher than that in the plain region, which will exacerbate the freeze-thaw damage process of railway concrete in the plateau region.

2.3.3 Durability improvement strategy. To prevent the impact of extreme low-temperature environments on the durability of concrete structures, insulation and curing techniques can be used during the construction phase of casting concrete to prevent early freezing damage to the concrete. During the service stage of concrete structures, steel casing can be used to isolate concrete from water for underwater piers of railway bridges, thereby reducing the impact of high-frequency freezing and thawing on concrete. The cast-in-place roadbed concrete can reduce the risk of surface freeze-thaw damage by timely cleaning the snow and/or water on the concrete surface.

2.4 The low-pressure environment

2.4.1 Environmental characteristics. The pressure of gas is generated by frequent collisions of a large number of molecules with the surface of the object. The ratio of the collision force of molecules to the area of action is the pressure of the gas. Therefore, the pressure of gas is related to altitude, atmospheric temperature and atmospheric density. As the altitude increases, atmospheric pressure usually decreases exponentially, as shown in Figure 15. For every 12 m increase in altitude, the atmospheric pressure will decrease by approximately 133 Pa. Compared with Beijing, the altitude of Lhasa in Tibet has increased by about 3,400 m, and the pressure has decreased from 100.21 to 65.2 kPa. Due to the average altitude of the Qinghai Tibet Plateau being above 3,000 m, the average environmental pressure is about 60% of that in plain areas. This special environment will have a significant impact on the pore structure characteristics and moisture transport process of concrete mixtures, which is a common problem faced by the durability of railway structural concrete in high-altitude areas.

2.4.2 Mechanism.

(1) The impact on the pore structure of cement stone

The pore structures of cement stone are important factors affecting the compressive strength, medium transmission rate and frost resistance of concrete. Mindess (Mindess, 2003)

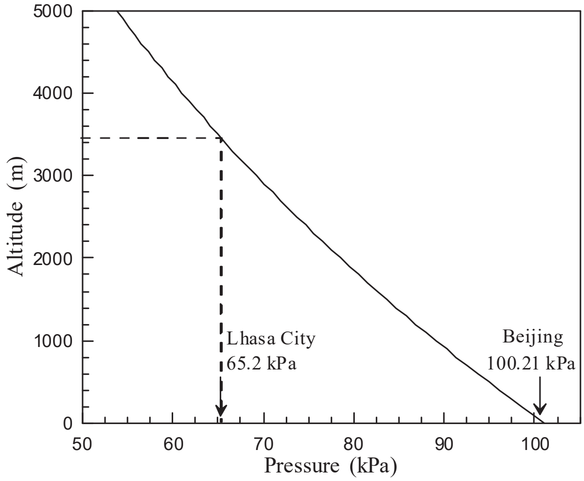


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Figure 15.
Variation curve of ambient air pressure with altitude

divides the pores in the hardened cement slurry into interlayer pores (≤0.5 nm) according to their pore size: micro pores (0.5–2.5 nm), independent small capillary pores (2.5–10 nm), medium capillary pores (10–50 nm) and large capillary pores (50–10,000 nm). Among them, interlayer pores, micro pores and independent small pores are called gel pores, which belong to harmless pores in concrete. The combination of meso pores and macro pores is called capillary pores, where meso pores with a pore diameter less than 50 nm are considered harmless and/or less harmful pores, while macro pores are considered harmful and/or more harmful pores. From this, it can be seen that the pore size in concrete cement paste is the key factor affecting the performance of concrete. In engineering practice, people usually introduce small, regular, closed pores into concrete through the use of functional additives to improve its workability, enhance impermeability and frost resistance.

However, the environmental pressure in the Qinghai Tibet Plateau region is only about 60% of that in plain areas. Under low-pressure conditions, the size of bubbles in concrete mixtures will also increase due to the increase in surface tension. After the bubble size increases, it will be easier for it to escape from the freshly mixed concrete. Bubbles that do not escape will remain in the concrete system and become pores in the concrete after hardening. Li, Wang, Xue, Bai and Wang (2021) conducted a study on the pore structure characteristics of concrete-hardened bodies under two pressure conditions of 100 kPa and 60 kPa using three types of air-entraining agents. The results are shown in Table 1.

Under low-pressure conditions, the average pore diameter and bubble spacing coefficient in concrete-hardened bodies significantly increase. When the ambient pressure decreases

Table 1.
Pore structure parameters of hardened concrete under different air pressure

No.	Average pore diameter (μm) $P = 60$ kPa	$P = 100$ kPa	Bubble spacing coefficient (μm) $P = 60$ kPa	$P = 100$ kPa
1	364.946	290.086	405.776	211.224
2	348.367	327.207	355.131	243.687
3	297.687	252.315	284.215	195.659

Source(s): Li, Wang, *et al.* (2021)

from 100 to 60 kPa, the average pore diameter will increase by about 6 to 25%, and the increase is related to the type of air entraining agent. The corresponding bubble spacing coefficient increases by about 50 to 90%, and the magnitude of the increase is also related to the type of air entraining agent. From this, it can be seen that the low-pressure environment on the plateau will reduce the air content in the concrete mixture. The pore size existing in the hardened body will also significantly increase. For the underwater piers, track bed structures and secondary lining concrete at tunnel entrances in railway engineering, a decrease in air content will directly lead to a decrease in concrete frost resistance, which is prone to durability problems such as surface peeling and powdering caused by repeated freeze-thaw cycles. At the same time, the increase in pore size in the hardened concrete will directly lead to a decrease in the impermeability of the concrete, making it easier for harmful media to invade the interior of the structural concrete, resulting in accelerated deterioration of railway bridge piers, secondary linings and track bed concrete.

(2) The influence of water transport and shrinkage deformation

During the service life of railway engineering structural concrete, it will undergo medium exchange with the surrounding environment. As the environmental humidity is usually lower than the humidity level of the capillary pores inside the concrete, the moisture in the capillary pores inside the concrete will diffuse into the surrounding environment under the effect of the humidity gradient. This process can be described by Formula (3).

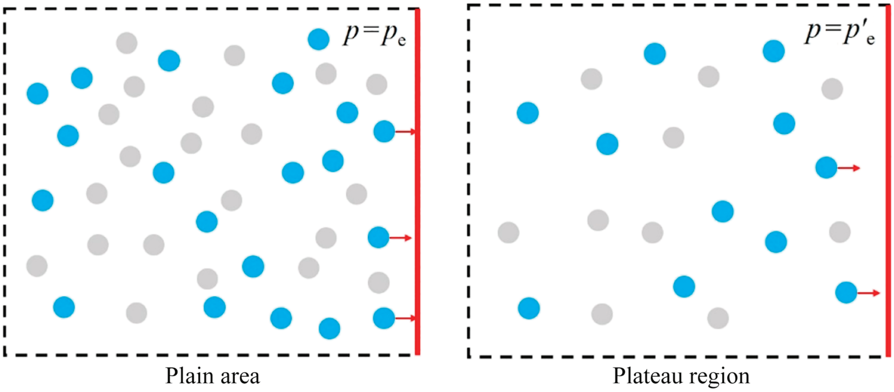
$$J = -\frac{D_m M P_s}{RT}\frac{dH}{dx} \tag{3}$$

In the formula, J is the water loss rate of concrete under drying condition (kg/m^{2}s), D_m is the diffusion coefficient of water vapor in air (m^2/s), P_s is the saturated vapor pressure of water at a given temperature (Pa), R is the ideal gas constant (J/mol K), M is the molar mass of water (kg/mol), T is the temperature (K) and H is the relative humidity of concrete. According to Formula (3), the water loss rate of concrete under drying conditions is directly proportional to the humidity gradient between its surface capillary pores and the environment. The variation of relative humidity in the internal capillary pores of concrete is mainly related to the curvature radius of its curved liquid surface. As cement hydration and drying processes continue, the moisture content in the capillary pores of concrete cement stone gradually decreases. The curvature radius of the curved liquid surface in the pores also gradually decreases. Correspondingly, the partial pressure of water vapor above the liquid surface also gradually decreases, and the relative humidity gradually decreases. The Kelvin equation can be used to describe the relationship between the curvature radius of capillary curved liquid surface and relative humidity.

$$H = \exp\left(-\frac{2\gamma M}{\rho r R T}\right) \tag{4}$$

In the formula, M is the molar mass of water (kg/mol), ρ is the density of water (kg/m^3), R is the ideal gas constant (J/mol K), ε is the surface tension of water (N/m), T is the temperature (K) and r is the curvature radius of the curved liquid surface (m). According to Formula (4), the relative humidity in concrete capillary pores is independent of environmental pressure conditions and is only related to the basic properties and curvature radius of the liquid in the pores.

However, the environmental pressure is mainly caused by irregular collisions of gas molecules in the environment. The environmental humidity level is mainly caused by collisions of water vapor molecules, as shown in Figure 16. Figure 16 (a) shows the principal diagram of pressure formation in plain areas and (b) schematic diagram of atmospheric



Plain area
(a)

Plateau region
(b)

Source(s): Authors' own work

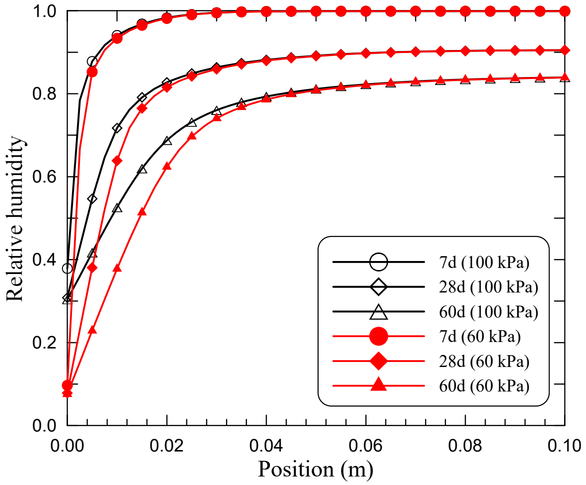
Figure 16. Schematic diagram of environmental pressure formation in plain and plateau areas

pressure formation in high-altitude areas. Among them, water vapor molecules are represented in blue, while other gas molecules are represented in gray. As shown in Figure 16, the air in high-altitude areas is thinner, the number of water vapor molecules per unit volume decreases and the partial pressure generated by the collision of water vapor molecules decreases. Therefore, the environmental humidity in plateau areas is lower than that in plain areas.

To further analyze the impact of a high-altitude low-pressure environment on the moisture loss and durability of railway structural concrete, this paper conducts theoretical research on the internal humidity distribution of railway bridge pier concrete under different environmental pressures based on the theory of moisture diffusion. Pay special attention to the radial distribution of moisture in the concrete of railway bridge piers at curing ages of 7 days, 28 days and 60 days under environmental pressure conditions of 100 kPa and 60 kPa, as shown in Figure 17.

The low-pressure effect on the plateau will accelerate the water loss of concrete near the drying surface of railway bridge piers, resulting in a lower relative humidity level than in plain areas. When the ambient air pressure decreases from 100 kPa to 60 kPa, the humidity level near the drying surface of concrete at all ages significantly decreases. However, the effect of high-altitude low pressure on the humidity level of concrete is mainly limited to a certain range near the drying surface, and its impact on the relative humidity inside the concrete is relatively small. With the extension of the curing period, the influence range of environmental low pressure on the relative humidity of concrete gradually expands and penetrates into the interior of the concrete pier body. The change in internal humidity of concrete is the essential influencing factor of its shrinkage deformation. The low pressure on the plateau not only affects the surface humidity level of concrete but also significantly accelerates the development of shrinkage deformation of concrete within a certain range of the drying surface of railway structures in plateau areas, thereby accelerating its cracking behavior.

2.4.3 Durability improvement strategy. Low air pressure is a common problem faced by concrete structures in high-altitude areas, and any concrete structure exposed to the high-altitude environment is affected by this environment. There is currently no good durability guarantee or improvement measure for this environment.



Source(s): Authors' own work

Figure 17.
Calculation results of moisture distribution along the radial direction of railway pier shaft under different air pressures

3. Conclusion

This article analyzes the mechanism of the impact of four special environments, namely large temperature differences, strong winds and dryness, high cold and low air pressure, on the durability of railway structural concrete in high-altitude areas through theoretical and experimental research. The corresponding durability improvement measures were proposed from the aspects of raw materials, mix proportions, construction control and maintenance measures. For further improvements, suggestions are provided from three aspects, namely theoretical research, new technology development and standard system to address the shortcomings of the durability guarantee system for concrete structures of high-altitude railways.

(1) Further improvement of the theoretical system of durability of concrete structures for high-altitude railways

For railway concrete in western mountainous areas of China, the special environmental characteristics are only one aspect that affects its durability. The special geological conditions in high-altitude areas (such as weak surrounding rocks, rockburst conditions, etc.) and the special load conditions of railway engineering (such as high-frequency train loads, aerodynamic effects of trains, etc.) are also important factors affecting the durability of concrete structures in high-altitude railways. The existing research mainly focuses on theoretical and experimental analysis of the influence of a single factor, which is not sufficient for a comprehensive analysis of the durability degradation mechanism of concrete in high-altitude railways. Therefore, it is necessary to conduct systematic research on the degradation mechanism of concrete durability of railway structures under the coupling effect of special environment, geological conditions and load conditions in the plateau and ultimately form a theoretical system for the durability of concrete in plateau railway structures.

(2) New technology for controlling concrete durability through construction

The key factors affecting the long-term durability of concrete include raw materials, preparation, construction and curing. However, the low quality of ground materials and difficulties in logistics transportation are practical problems faced by railway construction in high-altitude areas. It is very limited to improve the long-term durability of concrete only by optimizing raw materials and preparation technology in high-altitude areas. Therefore, in the construction of high-altitude railways, the durability of concrete structures should be further improved through intelligent construction control technology. For example, through surface vacuum curing, optimizing the structure of the drying surface of structural concrete, improving compactness and reducing the risk of concrete freeze-thaw damage and surface cracking.

(3) Improve the standard system for durability of concrete structures in high-altitude railways

In China's railway engineering standard system, there is currently no technical standard for ensuring the durability of railway concrete in high-altitude areas. At present, railway engineering in high-altitude areas is still mainly designed and constructed based on standards in plain areas, without considering the impact of special high-altitude conditions on concrete durability. The research results on the service status of completed high-altitude concrete infrastructure (such as the Sichuan Tibet Highway) show that the durability degradation rate of high-altitude concrete is generally faster than that of plain areas, and some structures have entered the maintenance stage too early. With the continuous advancement of railway construction in China, high-altitude railway projects in the central and western regions have gradually become the focus of railway construction, and the amount of high-altitude railway construction projects is enormous. Therefore, it is necessary to improve the durability standard system for concrete structures of high-altitude railways to ensure their safe and durable service.

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