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Concrete Crack of Ballastless Track Structure and its Repair

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Abstract

Crack and its damage of structure concrete in both FBS and TBS ballastless track are presented. The cause of concrete crack is analyzed. According to corresponding quantitative equation, effective technical measures to depression crack of concrete are put forward, at the same time the rationality of elastic ratio for HGT has been proved. At last, by the analysis of the characteristic of high-speed train, which are serving in the open air, bearing fatigue load, the short time for maintenance window and high speed of service, technical requirement for concrete repair material, repair technology and repair tools of ballastless track structure are presented.

***Keywords :** *Ballastless track, Concrete, Crack, Repair**

1. Introductions

Ballastless track is a track structural style whose roadbed with particulate ballast is replaced by the cement-base materials (concrete or cement asphalt mortar). With the spread of ballastless track technology, the field of application of concrete is expanded in the railway field. It is pity that the concrete crack phenomenon in the ballastless track has appeared widely in high-speed railway project abroad and domestic. In order to control crack width, critical values of crack width of ballastless track structural concrete are put forward by different country. For FBS ballastless track in Japan, repair specification is stipulated according to the concrete crack width, seen Table 1. The concrete critical crack width of TBS ballastless track is 0.5 mm in German, and no crack can be appeared in the range of the fastener.

Concrete crack has become study focus, however, there is a little research of concrete crack against the structural style of ballastless track and the characteristic of high-speed railway. The high-speed railway is known as widely dispersed, service in the open air, bearing fatigue load and the short time for maintenance window, which are the reasons for the particularity of concrete crack cause and the complex of repair technology in ballastless track. Based on the analysis of concrete crack case appearing in ballastless track project abroad and domestic, the cause for concrete crack and the corresponding countermeasures to restraining concrete crack are put forward. Feasibility of predicting concrete crack is discussed. In the end, combining with the characteristic of high-speed railway, technical requirement for repairing of ballastless track structural concrete are presented.

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2. Concrete Crack Case and its Damage in Ballastless Track Structure

2.1 Concrete Crack of FBS

Concrete crack of FBS include track slab and base concrete.

2.1.1 Crack in track slab

Track slab is a kind of precast concrete structure. Principle of the design of track slab is no crack design, but some cracks can be found in the track slab due to load action, environmental factor (such as temperature) and creep of concrete. Fig. 1 shows cracks in track slab. Longitudinal crack which is inducing by the non-homogeneous stress is easy to appear in the range of fastener. There are many cracks is in the inner side of frame track slab, and some cracks run through the total depth of track slab. Some cracks generate form lifting and some generate from steam curing system of track slab or the structure of track slab. It is reported, most of track slab cracks are induced by the alkali aggregate reaction and salt injury. Some track slabs have been changed in Japan.

2.1.2 Crack in base concrete

Base of FBS ballastless track is C40 reinforced con-

Table 1. Repair specification of FBS ballastless in Japan

Damage Part		Class	Critical value	Note
Track Slab	Crack	A	b ≥ 0.2 mm	b – crack width
		B	0.2 mm > b ≥ 0.1 mm	
		C	0.1 mm > b ≥ 0.05 mm	
	Defect, Crippling	A	Concrete iron exposed, Defect	
		B	Concrete iron exposed, Defect	
		C	Rustiness	
Concrete Orientation Desk	Crack	A	b ≥ 0.2 mm	b – crack width
		B	0.2 mm > b ≥ 0.1 mm	
		C	0.1 mm > b ≥ 0.05 mm	
	Defect, Crippling	A	Concrete iron exposed, Defect	
		B	Concrete iron exposed, Defect	
		C	Rustiness	

Note: Class A: Repair quickly; Class B: Prepare to repair; Class C: Notice, register in standing book.

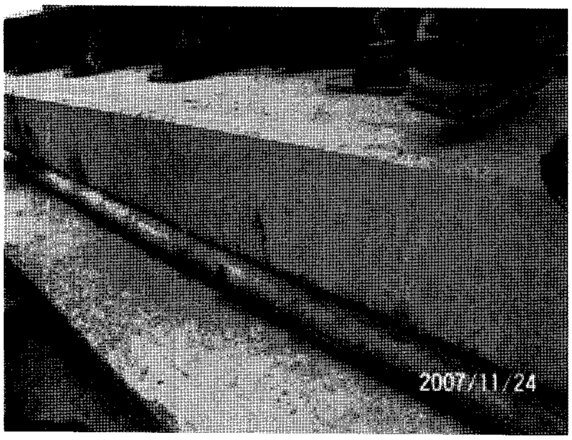
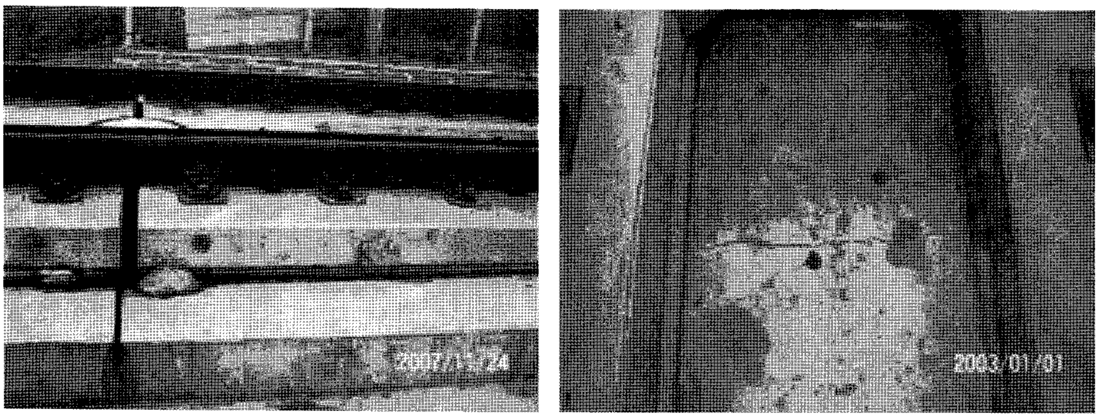


Fig. 1 Crack in track slab

crete structure. As a kind of bulk mass, base concrete must be cast continuously. Fig. 2 shows some cracks in the base concrete. Crack of base concrete is vertical with the roadbed. Along the track direction the cracks appear in periodic gap, and the interval is 5-15 m. Moreover, the depth of crack reaches the whole thickness of base. Some cracks appear in the position of the expansion joint and the crack extends down the expansion joint. Cracks can be found in the middle of the track slab, and the width of the crack reaches the total width of track, seen Fig. 2(b).

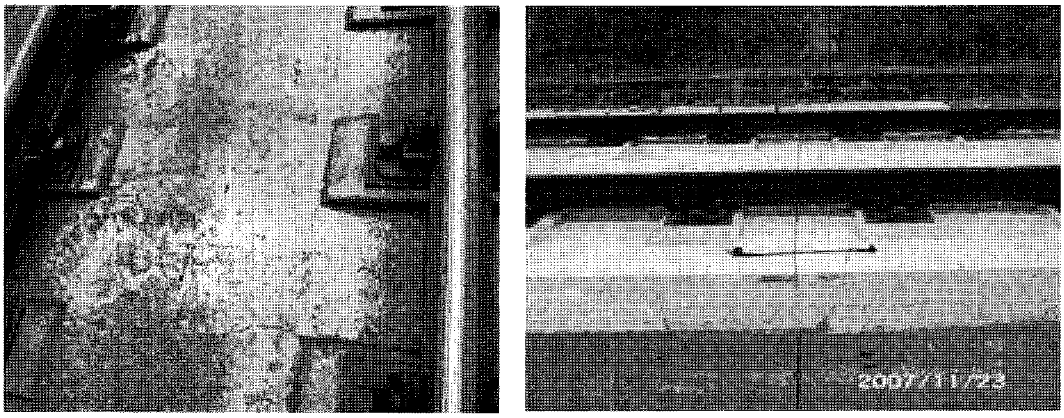
2.2 Concrete crack in the TBS ballastless struc-ture

Concrete cracks of the TBS ballastless structure appear in the roadbed slab and HGT.



(a) (b)

Fig. 2 Crack in the base concrete



(a) (b)

Fig. 3 Crack in roadbed slab

2.2.1 Crack in roadbed slab

In order to avoid crack inactivation of concrete structure due to tensile stress action, FBS ballastless track is designed according to the no stretching resistance principle, that is maintaining the structure in low or zero tensile stress as base principle of design. There are many cracks in roadbed slab concrete, due to interface between the old (sleeper) and new concrete (roadbed slab concrete), seen Fig. 3. There are two kinds cracks in roadbed slab, one of the cracks appear in the four corner of sleeper, splayed crack universally occur in the interface between the corner of the sleeper and the roadbed slab concrete. The cracks between the corresponding twin block sleepers become into one crack cross-over the whole roadbed slab, seen in Fig. 3(a). And the other crack is cross direction or oblique direction cracks, some of them lie in the position of the expansion joint, seen Fig. 3(b). Along the cast direction of the concrete, cross cracks appear interval.

2.2.2 Crack in HGT

HGT with the function of stress dispersion, load transfer, rigidity decrease has become the necessary part in the ballastless track. Corresponding qualifications for different track structure such as TBS ballastless track (Züblin type-Rheda2000 type) and FBS ballastless track (Bögl type) are put forward. The difference between HGT material and concrete is the elastic ratio. For kinds of reasons, there are many crack phenomenons in the HGT; on the contrary, these cracks become the cause for the crack appearing in the roadbed slab. Periodic cracks of the HGT distribute along the casting direction. There are two or three cracks between two expansion joints. Depth longitudinal cracks with crack width more than 0.5 mm lie in almost every position of the expansion joints, and become a cutting through crack with the crack in the roadbed slab.

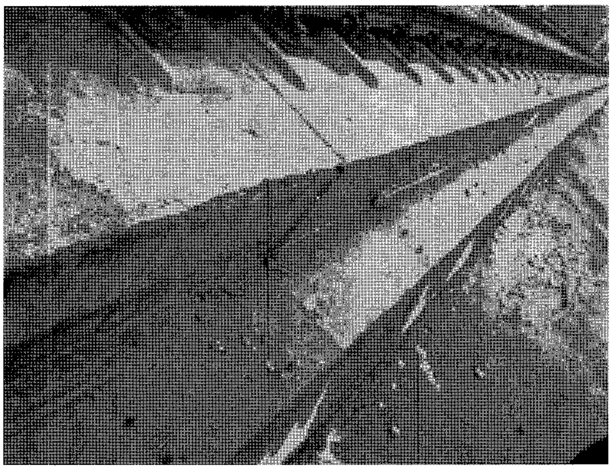


Fig. 4 Crack in the HGT

2.3 Damage of the concrete crack in ballastless track structure

There are two kinds hazard in ballastless track, one is reducing durability of track structure and safety of train travel, the other is inducing insulation inactivation of insulated node.

Cracks in the track slab and roadbed slab will become the entryway of the corrosion substances. Under the Cl^- or CO_2 environment, the steel in the slab will be corrosion, and expansion of the productions of corrosion will aggravate the crack of the concrete, sequentially reducing the durability of the concrete structure. For TBS ballastless track, due to different produce process and deforming property between the preforming sleeper and new filling concrete, binding property of concrete in the joint is poor. Under movable load, concrete of roadbase slab is easy to disintegrate and the sleeper rap, which affect the safety of the train. No crack should lie in the range of fastener; else the cracks will introduce the fastener loose, thus affect track structure stability. In addition, there may be potential incipient fault of travel.

For ballastless track structure, concrete cracks not only do harms to the crack concrete, but also do harms to the conterminal part. Cracks in the base concrete and HGT will be the pathways to the water. Immersing the water for a long time, the roadbed accelerates falling in, at the same time increase sedimentation value of base, thus affect the stability of base and reduce the durability and bearing capacity of roadbase. Moreover, the cracks in base concrete aggravate corrosion of its steel. Cracks in HBT will become reflect crack which aggravates the crack in roadbase concrete.

In addition, there are insulation latch hooks around the steel in the slab. Be some cracks in track slab structure, the water is easy to permeate in the inner of the concrete, and the water in the crack evaporates very slowly. So in the rain weather, much water accumulates in the crack, which makes the insulation latch hook in the insulation mode inactivation, insulation property fall down gradually, what may be affect the travel safety for the electrification train.

3. Crack Cause and its Countermeasures for Ballastless Track Concrete

The condition of concrete crack is that the tension stress generated by deforming under restraint is bigger than its strength of extension, and then the crack happens. Therefore, the condition influencing the concrete crack includes the deformation size, the degree of restraint, and the real-time strength of extension. The expansion energy of old crack is far smaller than that of newly generated crack, so the main solution for preventing concrete crack is to control concrete crack in early stage.

3.1 Crack caused by drying shrinkage

Crack caused by drying shrinkage is caused by the dry shrinkage deformation of concrete, which often happens after some time of finishing the curing concrete or after finishing concrete casting one week or so even more time. The evaporation of water in the concrete paste will produce dry shrinkage which is a non-reversible process. In the common condition, the dry shrinkage deformation of aggregate is very small, which may be neglect. The dry shrinkage deformation of hardened cement stone is big, which is often several hundred of micronstrain, even thousand of micronstrain. When the concrete dry shrinkage deformation strength is bigger than stretching resistance of concrete resisting external, the crack will happen in the concrete. The formula of the concrete dry shrinkage deformation is No.1 formula.

$$\varepsilon_s = \varepsilon_{cs}\left[1-\frac{V_a^{1/3}}{1+\frac{E_c}{E_a}(V_a^{-2/3}-1)}\right] \qquad \text{Formula (1)}$$

In No.1 formula

ε_s – dry shrinkage deformation of concrete;

ε_{cs} – dry shrinkage deformation of hardened cement stone;

V_a – volume content of aggregate;

E_a, E_c – elastic modulus of aggregate and hardened cement stone.

If the dry shrinkage of concrete is reduced, the crack will be reduced or not happen at all. According to No.1 formula, the following solution will reduce the dry shrinkage of concrete:

(1) Reducing the cement stone content in the concrete. Cement paste component is be reduced in the concrete system, that is reducing cement and unit of using water and increasing aggregate volume content in the concrete system. Reduction the component in the cementitious material which shrinkages largely when becomes hardened, that is applying the prime mineral admixtures instead of cement or reducing w/cm.

(2) The more the elastic modulus ratio of aggregate and hardened cement stone, the smaller the dry shrinkage deformation of the concrete. Therefore, choose the hard texture and high elastic modulus ratio of aggregate as possible as we can. Furthermore, the effective method to reduce the elastic modulus of cement stone is to add prime mineral admixtures, especially the prime fly ash.

(3) Reinforce curing. It needs not only in time curing but also sufficiently curing, which means the time of curing must be long enough. Reinforcing curing can guarantee the strength development of the concrete and the hardened cement stone. Moreover sufficiently curing may also put off the time of dry shrinkage and release the degree of the dry shrinkage. The action on both sides makes the dry shrinkage happen after the concrete and the hardened cement stone have enough resistivity, so that the dry shrinkage crack of concrete may be avoided efficiently.

In order to reduce concrete crack in FBS of the SUIYU test project, the proportion of the concrete for roadbed concrete has been adjusted several times successively, which can be seen in the No.2 table. The general trains of thought is to reduce the cement content in the cementitious composition, add the content of the fly ash as prime mineral admixture, reduce the content of the cement stone in the system, add aggregate content in the system and reduce unit water content in the concrete. The No.3 pro-

Table 2. Concrete composition of roadbed slab in SUIYU test line

material name	cement	fly ash	coarse aggregate	Fine aggregate	water	addictive	swelling agent
No.1 kg/m^3	365	60	1216	582	174	7.67	0
No.2 kg/m^3	315	135	1216	524	170	9.9	45
No.3 kg/m^3	320	125	1290	534	155	7.67	0

portion after being adjusted reduces the concrete crack in the roadbed slab greatly.

3.2 Crack caused by the change of temperature

Temperature crack is a kind of crack caused by the temperature changing in the concrete structure or non-uniform temperature distribution. The temperature changing and non-uniform temperature distribution may be divided into interior and exterior temperature difference. The former difference is caused by heat of hydration delivered by hydration action of cementitious material, and the latter is caused by the environmental temperature changes which the ballastless track structure is posited in. The surface cracks in the temperature crack usually appear during the time of construction. The deep and penetrating one often happens two to three months even more after concrete casting, for example, the crack in base structure and HGT, which parallels or near with the structural member or the short edge of the structural member, and appears sectionally along the track. At the same time the width of the crack changes with the season, and the crack is wide in the winter and narrow in the summer. Generally thinking of the destroy strength in the concrete and the resistance of itself may get the approximate condition that guarantees the basic concrete not generating penetrating crack as following No.2 formula.

$$\frac{K_P}{1-\mu}[\alpha A_1(T_P-T_f)+\alpha A_2 K_r T_r+A_1\varepsilon_s+A_1\varepsilon_a\eta]\le\frac{\varepsilon_P}{K}$$

Formula (2)

In No.2 formula:

K_P – stress relaxation coefficient of the concrete;

μ – Poisson ratio of concrete;

T_P – casting temperature of concrete;

T_f – concrete temperature, $T_P - T_f$ called uniform temperature difference;

K_r – thinking the stress reduced coefficient caused by the action of concrete temperature rise in the early stage, usually taking 0.7-0.85;

η – thinking the reduced coefficient caused by the volume deformation of concrete itself with the age developing, smaller than 1. If expanding or shrinkage mostly happens in the early stage, we will take the low value. Otherwise, when expanding or shrinkage mostly happens in the late stage, we will take the high one.

ε_s – dry shrinkage deformation of concrete;

ε_a – volume deformation of concrete itself, expanding take the negative value, and shrinkage take the positive one;

$A_1=0.690-0.195\frac{E_c}{E_R}+0.025\left(\frac{E_c}{E_R}\right)^2$ – restraint coefficient of uniform temperature difference in casting block;

$A_2=0.472-0.1567\frac{E_c}{E_R}+0.023\left(\frac{E_C}{E_R}\right)^2+3.72\times10^{-3}L-9.63\times10^{-6}L^2$ – restraint coefficient non-uniform temperature difference in casting block, E_R – basic elastic modulus, L – length of the casting block.

Taking concrete of roadbed slab, HGT as the question of the flat face one to discuss , formula of temperature stress σ_t can be expressed by No.3 formula,

$$\sigma_t=\frac{K_pE_c\alpha A_1(T_p-T_f)}{1-\mu}+\frac{K_pE_c\alpha A_2K_rT_r}{1-\mu}$$

Formula (3)

According to the restraint coefficient of uniform or non-uniform temperature difference of the casting block, No.3 and No.4 formula, the solution reducing the destroy stress is as following:

(1) Reducing restraint resistance and the elastic modulus of the basic concrete. The smaller A_1 and A_2 is, the smaller the temperature destroy stress is. Taking E_C/E_R as independent variable, the extreme value can be gotten from equation A_1 and A_2. When E_C/E_R 3.9 and the other condition are between 3.4and are fixed, A_1 and A_2 is the smallest. Taking the example of TBS, concrete in the roadbed slab is usual C40 concrete. According to the design performance of the concrete structure (GB 50010-2002), when concrete is stressed or stretched, the elastic modulus of C40 concrete may be 3.25×10^4 MPa. If following the smallest value of the temperature destroys stress, the elastic modulus of the bearing layer material should be 10000-8000MPa. Therefore, the technology condition of HGT in Germany which compressive strength is 15MPa and the elastic modulus is 10000 MPa (according to the design performance of concrete structure, the elastic modulus of C15 concrete should be 2.20×10^4 MPa) is appropriate, so that the crack of HGT and reflective crack in roadbed slab caused by crack in HGT can be reduced as possible.

(2) Properly stratify and block, proper set construction

joint. The relation of temperature destroys stress and non-uniform temperature difference restraint coefficient is secondary inverse function. Taking the casting length as the independent variable the extreme can be gotten from the non-uniform temperature difference restraint coefficient. In the scale of 193m in the continuous building, with the casting length increase, the coefficient of non-uniform becomes big and the temperature destroying stress becomes large. Properly setting construction joint in the HGT layer of the TBS ballastless track and base concrete structure of the FBS ballastless track is an effective way to reduce crack. Construction joint has been set in HGT construction project. Most of the construction joint can be found every 5-6 m. Proper distance between construction joint determined needed to associate with material and real simulating experiment.

(3) Reducing the temperature difference of uniform and non-uniform. Temperature destroying stress and uniform temperature difference and non-uniform one presents positive relation. The bigger the temperature is, the bigger the destroy stress caused by temperature. Caused by hydraulic heat, non-uniform temperature difference reduced is to reduce hydraulic heat of cement by add mineral admixture, which may improve work performance and durability of concrete and at the same time reduce effectively hydraulic heat of concrete and put off peak value of hydraulic heat, and Table 2 shows the case. In the precondition of fixed addictive content, adding fly ash content and reducing cement content can reduce the use of water, reduce hydraulic heat, and put off the time of hydraulic temperature rise peak value. Reducing uniform temperature difference of concrete is to properly construction organization and make the difference between casting heat and stabilizing temperature of concrete smallest. Especially pointing, it's the temperature difference which causes concrete crack instead of temperature.

3.3 Crack caused by plastic shrinkage

Plastic shrinkage crack form due to water quick lost by many factors, which include atmosphere, temperature of concrete, relative moisture and the surface wind velocity in concrete. Plastic crack can be easily influenced by temperature, wind velocity and moisture. In the condition of high wind velocity, high temperature and the low moisture in the environment, it's easy to form this kind of crack. After concrete initial setting, concrete just form structure and lose flowing power, but its force is very slow. In this period, more water lost will create large plastic shrinkage. Crack will happen in concrete which has no ability of resistance shrinkage stress. Plastic crack is a kind of distribution shape in random and multilateral. These crack in surface is fairly wide, the width of which is from several inch to several foot. Plastic crack in surface of road bed slab, base concrete surface and HGT surface may happen. The influence of plastic crack is not severe for the standstill building, but it's different for the ballastless track structure. The passing train will make plastic crack open and close repeatedly, and lead width of crack to develop continuously.

The solution of reducing the plastic crack in concrete of ballastless track structure is as followings:

(1) Reinforcing curing, especially the curing in the early stage, in order to avoid water lost in early stage. Concrete of road bed slab, HGT concrete and base concrete are level face plat. Because there is big area contacting with the environment, it's more easily to evaporate for water in concrete. Construction under environment of high temperature and big wind, more effective solution should be taken.

(2) Choose proper component of cement or cementations material, and control the time interval between initial set and final set. Before initial set, concrete in shape of flowing can't create crack, but when it lost flowing power the crack will happen because of strength not enough to resist its shrinkage stress. Therefore, when choose cement, choose short time interval between initial set and final set concrete.

4. Discuss on Cracking Prediction of Concretes of Ballastless Track

Today, with the rapid development of express railway technology, whether the advanced technology and mathematic theory can be used to predict early cracking of concretes of ballastless track will be the new topics about restraining that cracking. It is stated by Springenschmid, prevention of concrete early cracks is one of the main problems of concrete technology. Using modern concept to predict the concrete strains and their influences in early age is one substitute for those methods only based on experiences. F. Czerny carried out the research on safety factor for preventing concrete from cracking in early age through probability theory. Yuan established the formula of early concrete cracking related to thermal stress, dry shrinkage and creep.

Base on structural credibility theory, Yan *et al.* built up the model about early cracking of concrete structure considering randomness of the series of factors such as self-constricted, heat of hydration and degree of structure restrain of concrete. The prediction outcomes can provide evidences for material selection of concrete. Applicability of the forecast model of concrete structure cracking is proved by a 110m earth-retaining wall in one subway.

Some researchers put forward the technical analysis on probability theory of concrete cracking, defining C as the ratio between tensile stress and tensile strength updating. The calculation formula is shown as formula 4 considering thermal shrinkage stress and dry shrinkage stress. When C≤40%, small risk of cracking; when C∈40%-60%, moderate risk; when C≥60%, high risk.

$$C = C_1 + C_2 = \frac{1}{f_t}(A\sigma_{sd} + BH_tE_c\alpha\Delta T) \times 100\% \quad \text{Formula 4}$$

In formula 4:

C – probability of concrete cracking;
C_1 – probability of cracking due to dry shrinkage;
C_2 – probability of cracking due to thermal shrinkage;
A – experimental constant related to age;
B – constant related to constraint degree;
σ_z – expansion stress, negative, MPa;
σ_{St} – thermal shrinkage stress, positive, MPa;
E_c – timely elastic module of concrete;
α – thermal expansion factor of concrete, 1/°C;
H_t – stress relaxation parameter, its value is 0.283;
ΔT – temperature difference of concretes, °C;
T_2 – temperature inside concrete, °C;
T_1 – lowest temperature of circumstance, °C.

There are still not reports about prediction methods on structural concrete cracking of ballastless track. It is very important to prevent structural concrete cracking of ballastless track and make sure the safety of ballastless track structures that relative prediction method has been studied considering the practice of high-speed railway project. That will be the new focus of researches on structural concrete of ballastless track.

5. Technical Requirements for Repairing of Structural Concrete of Ballastless Track

The new requirements about material, technology and equipments for structural concrete repairing of ballastless track have been put forward based on the working characteristics of high-speed railway, such as exposed service condition, periodical fatigue load, short time demand of maintenance window, and the high transportation speed.

(1) To satisfy exposed service condition, the repair materials should have the character of moisture-hardening, high elasticity and high durability. The repairing materials should be consolidated in wet condition, and of high elasticity and durability. All the concrete structures will be exposed in the open air. Much water will exist in the cracks, so that the repairing materials should be consolidated in humid condition. Changes of weather, temperature difference and others will influence the crack development. So the materials should have good elasticity and low contractility. Ballastless track always endure wind and rain blowing, sun drying and krystic accumulation, in addition, high-speed railways in China with the character of wide distribution and long span cover complex geology and climatic environmental. For example the PDL form Harbin to Dalian will face the severe cold weather and chloride ion corrosion. The High-speed railway from Beijing to Shanghai under construction covers high concentrate alkaline soil, where the concentration of Cl^- and SO_4^{2-} are up to grade H3 and H4. Moreover, the concrete structures face the severe cold weather which belongs to grade D2 and D3. The concrete structures of ballastless track will suffer different kinds of weathering attacks, which need high durability repair materials fit for different corrosion conditions. The different surrounding conditions require different durability of concrete structures. Therefore, special repairing materials should be worked out.

(2) To meat with periodical fatigue load, the repair materials should have high binding strength and elasticity. The repetitive open and close of cracks will happen due to the periodical fatigue load from express trains. Therefore, the repairing materials should have these abilities to prevent cracks along where has been repaired when express trains pass.

(3) To meat with short time demand of maintaining window, the repairing materials should have high early strength and rapid consolidation. No halt of the transportation is another difficulty of the repairing work. In the related specification (Temporary provisions of design for High-speed railway from Beijing to Shanghai), it is required that the total repairing time should be not more than 4 hours. The most obvious difference between railway and road is that the repair work for railway can only be carried out in one track. So these abilities are required for accomplishment of repairing within time of maintaining window.

(4) Been the high transportation speed, simple repairing technology and portable equipments are required. High-speed railway has the very high speed of service, such as design running speed of Jinghu high-speed railway is 350 km/h. The large attractive power originate from the high speed train is very large. Usually, the repair work can not be done in the site when the trains pass. The other thing, the most obvious characteristic of ballastlesas track is the integrity. So when carrying out the maintenance, any parts can not be got out and repaired individually. Thus, the equipments should be portable and automatically.