Study on Fatigue Characteristics of Concrete Sleepers with Porous Basalt as the Aggregate

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Abstract: Due to the shortage of local materials, porous basalt was used as the coarse aggregate in the prefabrication of sleepers for the Mombasa-Nairobi Railway in Kenya. To study their fatigue characteristics, the sleepers were measured under fatigue loading for their local strain, overall deformation and crack initiation. The methods used include the traditional strain measurement, the sleeper deflection measurement and the 3D optical strain measurement. To be more specific, the traditional strain measurement method was employed to compare the strain-load relation of the sleepers under different cyclic loading times. Deflection variations of the sleepers were taken into consideration to analyze sleeper local defects and the variation law of the constitutive relation for concrete. And the 3D optical non-contact strain measurement method was adopted to monitor the sleeper crack initiation and growth process under fatigue loading and analyze the crack growth law.

Keywords: carrying capacity; concrete sleeper; crack; fatigue characteristics; porous basalt

1 INTRODUCTION

Under the Belt and Road Initiative (BRI), China's railway construction technology has been introduced to East Africa. The Kenyan Mombasa-Nairobi Railway built by a Chinese company was completed and opened to traffic on May 31, 2017. The entire railway line was constructed subject to China's Class I Railroad standard. The Nairobi-Malaba Railway is an extension of the Mombasa-Nairobi Railway to northwestern Kenya, following the same standard class.

To achieve localized railway engineering construction and drive local economic growth, local raw materials were selected by the Chinese contractors as long as their properties meet requirements. In general, precast prestressed concrete sleepers are made of high-performance concrete for it has a really high strength. Before the fabrication of prestressed concrete sleepers in East Africa, the porous yet high-strength basalt was selected as the coarse aggregate through comparative studies. There is only a little referential experience worldwide of the application of the porous coarse aggregate to high-performance concrete [1]. Franesqui improved volume stability of asphalt concrete with porous volcanic rock aggregate, which was mainly functional material with no or very light load [2]. Previous research shows that various raw materials of the porous basalt aggregate concrete comply with the relevant technical regulations in the Railway Concrete (TB/T 3275-2011, Chinese Standard) and Standard for Constructional Quality Acceptance of Railway Concrete Engineering (TB 10424-2010, Chinese Standard) [3]. Preliminary static load tests also indicate that voids in basalt do not affect the static load test values of the concrete sleepers [4]. However, further study is needed to see whether voids in the porous basalt aggregate will adversely affect the durability of the sleepers. Therefore, it is of great engineering significance to study the fatigue characteristics of the concrete sleepers with porous basalt as the aggregate.

So far, scholars at home and abroad have done certain research on fatigue properties of concrete sleepers. In the study of Guo Runping [5] on the fatigue crack growth characteristic of the concrete sleepers with porous basalt as the aggregate, the results show that their crack width index meets the requirements of China's current codes. Jiang Xiaojun [6] took into consideration the possible problems of porous aggregates for sleepers and analyzed the causes of sleeper corner removal, edge chipping, and shoulder cracking. Based on damage investigation and test results of concrete sleepers [7] analyzed the effects of cracks on the durability of concrete sleepers. As [3] pointed out, an optimized concrete mix ratio and a complete concrete curing regime and system can improve the compressive strength and elasticity modulus of concrete sleepers with porous basalt as the aggregate, and increase their strength and durability [8]. Proposed that additional steel slag in the materials can improve the strength and durability of concrete sleepers [9]. In the fatigue experiments on steel fiber concrete sleepers by [10] they found that steel fiber concrete sleepers have better fatigue resistance than ordinary ones [11]. Found through experimental research that the addition of blast furnace slag and steel fibers can improve the bending resistance of concrete sleepers [12]. Analyzed the crack growth law of concrete sleepers under impact loading [13]. Studied the fatigue crack growth characteristics of steel fiber concrete sleepers under fatigue loading.

The failure of concrete sleepers is mainly due to the crack-caused durability problem of concrete structures [14]. China's existing Test Method for Fatigue of Prestressed Concrete Sleepers (TB/T1878-2002) is a code formulated for ordinary prestressed concrete sleepers for standard railways. There is no report about fatigue tests of the concrete sleepers with porous basalt as the aggregate, and their fatigue characteristics remain to be further studied [15].

In this paper, the concrete sleepers with porous basalt as the aggregate are taken as the research object for fatigue property tests. Though the tests, voids in basalt aggregate are analyzed for the effect on the availability of sleepers, and the fatigue characteristics of concrete sleepers are studied.

Main raw materials for sleepers: (1) Cement : Kenya Bamburi cement, CEMI 52.5 ordinary portland cement; (2) Sand : Kenya Sultanhamud sand field, medium sand (river sand). (3) Gravel : 5 - 20 mm continuous graded crushed

stone in Simba quarry from Kenya, porous basalt aggregate (Fig. 1a), porous, where, it should be noted that some pores in aggregate are more and some pores are less.

Sampled from the porous aggregate sleepers, the internal structure of three-dimensional reconstruction is obtained by X-CT FIGS, reuse of X-CT slice data were analyzed using the commercial software VGStudio. According to statistics, the average porosity of aggregate accounts for about 0.87%, and the distribution is uniform, which basically does not affect the strength of concrete. Fig. 1b is a sample, and Fig. 1c is a 2D slice diagram of the sample. In order to facilitate the analysis of the changes in the coarse pores on the aggregate, the VG software is used to render the aggregate in red and the slurry in gray. It can be seen that there is a certain amount of gray paste inside the red aggregate, indicating that the slightly larger aggregate is filled with paste. The filled paste will not only strengthen the strength of the aggregate after hardening, but also act as a "pin".
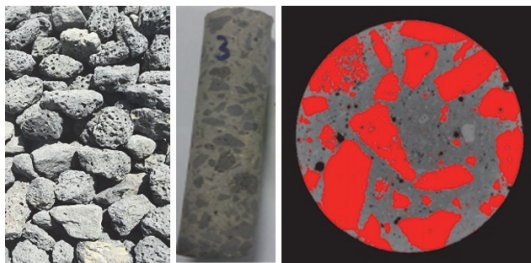
(a) porous aggregate   (b) sample   (c) 2D slice figure
Figure 1 Microscopic characteristics of porous aggregate

2 RESEARCH SCHEME OF FATIGUE PROPERTY OF THE SLEEPERS

In the fatigue tests of the concrete sleepers with porous basalt as the aggregate, the traditional strain measurement method was employed to measure the sleepers strain and figure out the sleepers strain-load relation under different cyclic loading times. The static deflection values after different cyclic loading times were measured by a dial gauge and used to analyze the sleepers' local defects and the variation law of the constitutive relation for concrete. The 3D optical non-contact strain measurement method was adopted to monitor the sleepers crack initiation and growth process under fatigue loading and analyze the crack growth law. Based on the above three aspects, the fatigue characteristics of the concrete sleepers with porous basalt as the aggregate are comprehensively analyzed.

In the literature [4], the concrete sleepers with porous basalt as the aggregate used in the Mombasa-Nairobi Railway were tested for fatigue according to the Chinese standard Test Method for Fatigue of Prestressed Concrete Sleepers (TB/T1878-2002). This proves that it is feasible to adopt this standard to test the fatigue property of the concrete sleepers with porous basalt as the aggregate. The sleeper fatigue tests in the paper are also subject to this standard.

2.2 Test Equipment

According to the Test Method for Fatigue of Prestressed Concrete Sleepers (TB/T1878-2002), the fatigue test machine with an accuracy of Class I is used for loading in the tests. Strain gauges are used to measure the strain at different heights within 5 cm from the rail spike on both the left and right sides (along the longitudinal direction of the sleepers), as shown in Fig. 2. Displacement dial gauges are used to measure the deflection at the section under rail, as shown in Fig. 3. The GOM-ARAMIS 3D optical strain gauge and the HPCS-1 crack width gauge are used to measure the length and width of cracks, as shown in Fig. 3. The main bar is also shown in Fig. 3.
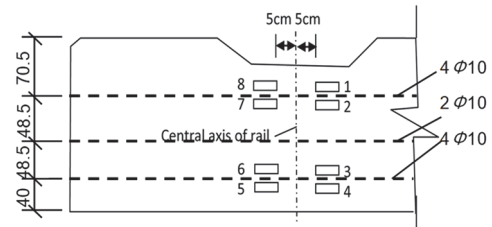

Figure 2 The locations of strain gauges (unit: mm)

The concrete sleepers with porous basalt as the aggregate are prefabricated according to the Chinese standard new II type sleeper design drawing [4].

It is 2.5 m in length, 20.2 cm in height under rail, 16.5 cm in middle section height), section width is 29.45 cm, under rail section width is 28 cm, and middle section width is 25 cm.

In the tests, six concrete sleepers with porous basalt as the aggregate of the same quality and same batch are used, numbered W1 to W6. Sleepers W1 to W3 are for the fatigue characteristics in the section under rail, while sleepers W4 to W6 are for those in the mid-sleeper section. Special note: The section under rail here refers to the sleeper area below the steel rail, which may suffer vertical cracks due to the load of the train; the mid-sleeper section here refers to the middle area of the sleepers, which may suffer vertical crack damage due to the bed support reaction.
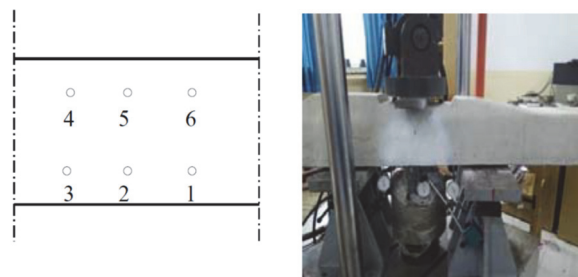

Figure 3 The locations of dial gauges

2.3 Test Design

Before fatigue cyclic loading, pre-loading is required to check whether the experimental equipment works normally. The fatigue cyclic loading is in the form of a sine

wave with a frequency of 7 Hz and 2×10^6 times of loading. The section under rail has a maximum and a minimum vertical load of 180 kN and 36 kN respectively; the mid-sleeper section has a maximum and a minimum vertical load of 135 kN and 27 kN respectively.

After the fatigue tests start, step-wise static loading and unloading are performed every 500000 times of fatigue cyclic loading to collect the strain data of the strain gauges and measure the sleeper deflection with dial gauges.

In the early stage of cyclic loading, the area loaded is measured by the GOM optical strain gauge every 10000 times, with the crack growth observed through image data processing. After an accumulation of 50000 times of loading, measurements are performed every 100000 times.

3 TEST RESULTS AND ANALYSIS

After 2 million times of fatigue cyclic loading, except for sleeper W3 which has no crack developed, sleepers W1, W2, W4, W5, and W6 all have a final crack width that does not reach the standard failure level as stipulated in TB/T 1878-2002. In the following text, sleeper W1 is taken as an example to analyze the fatigue property of the section under rail; sleeper W4 taken for that of the mid-sleeper section.

3.1 Strain Characteristics of Sleepers Under Cyclic Loading

The variation law of the strain at each measure point of the section of sleeper W1 under rail with static load is shown in Fig. 4. As can be seen from the figure, compared to the value before cyclic loading, after 2 million times of cyclic loading, the strain value at each measure point under the same static load basically remains unchanged. The sleeper strain-load relation does not change before and after fatigue loading, and the sleeper deformation and stress still show a linear relation, without a sudden change in stress. These fully show that the peripheral detail structure around the voids does not have significant changes; and that under fatigue cyclic loading, the voids in the coarse aggregate do not significantly change the mechanical characteristics of the section under rail. After 2 million times of cyclic loading, the strain returns to zero after static loading and unloading. This indicates that the sleeper still has the ability to resist elastic deformation, and that the overall mechanical properties of the area of the sleeper under the rail remain stable.

The relation curve between the strain at each measure point of the middle section of sleeper W4 and the static load value is as shown in Fig. 5. As can be seen from the figure, compared to the value before cyclic loading, after 2 million times of cyclic loading, the strain value at each measure point under the same static load increases, though slightly. The sleeper strain-load relation is unchanged before and after fatigue loading, and the sleeper deformation and stress still show a linear relation, without a sudden change in stress. These show that the local mechanical property around the voids is stable, and that under fatigue cyclic loading, the voids in the porous basalt coarse aggregate concrete do not significantly change the local mechanical characteristics of the mid-sleeper section. After 2 million times of cyclic loading, the strain returns to

zero after static loading and unloading, indicating that the sleeper still has the ability to resist elastic deformation, and that the overall mechanical properties of the mid-sleeper section remain stable.
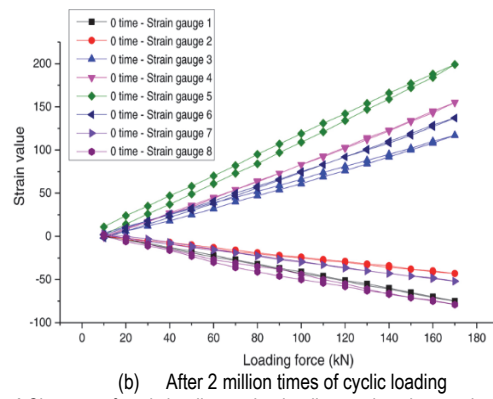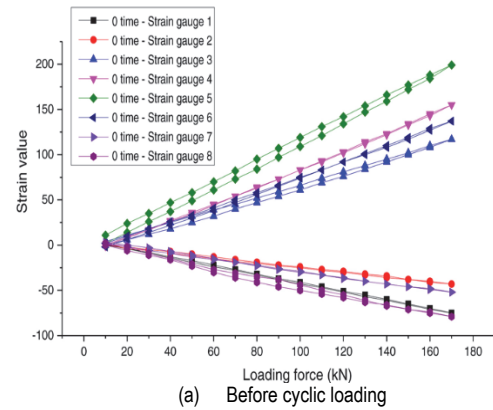

(a)   Before cyclic loading

(b)   After 2 million times of cyclic loading
Figure 4 Changes of static loading and unloading strain values at the measure points of sleeper W1

(a)   Before cyclic loading
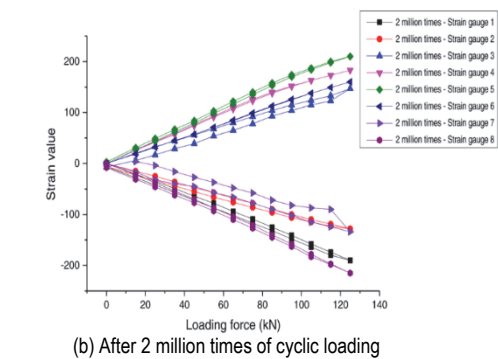

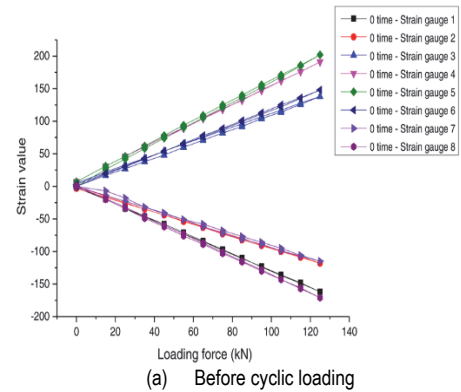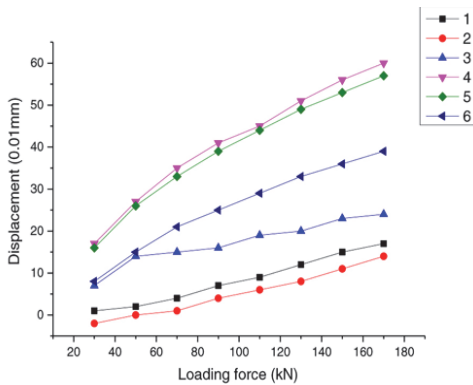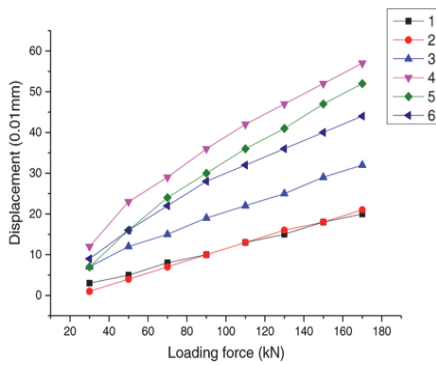(b) After 2 million times of cyclic loading
Figure 5 Variation of strain value of W4 under 2 million times of cyclic loading

3.2 Variation Law of Sleeper Deflection Under Cyclic Loading

The relation between the deflection at each observation point of the section of sleeper W1 under tail and the static load value is as shown in Fig. 6. As can be seen from the figure, compared to the value before cyclic loading, after 2 million times of cyclic loading, the deflection value at each measure point increases slightly under the same static load, which is because cracks appear on the section under rail after cyclic loading. The slight increase in deflection indicates that the sleeper's ability to resist elastic deformation after cyclic loading is basically unchanged, and that its carrying capacity does not reduce significantly. Before cyclic loading, the deflection and the loading force at each observation point are basically in linear relation; after 2 million times of cyclic loading, the deflection and the static load at each observation point still change linearly. As the results above show, for the section under rail, no obvious damage occurs around the voids in the porous basalt aggregate after fatigue loading; the local mechanical properties around the voids keep stable; and the voids have no effect on the overall mechanical properties of the sleeper.
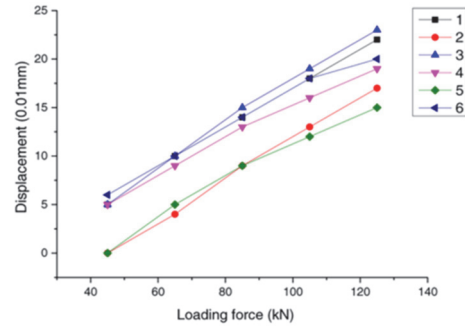

(a)   Before cyclic loading
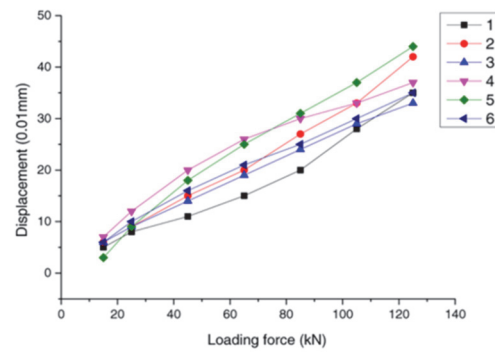

(b) After 2 million times of cyclic loading

Figure 6 Variation law of deflection at each observation point of sleeper W1 under stepwise static loading

The relation curve between the deflection of each observation points in the middle section of W4 sleeper and the static load value is shown in Fig. 7. As can be seen from the figure, compared to the value before cyclic loading, after 2 million times of cyclic loading, the deflection value at each measure point increases to some extent under the same static load, which is because cracks appear on the mid-sleeper section after cyclic loading. After 2 million times of cyclic loading, the deflection of each observation point and the static load value still change linearly. As the results show, for the mid-sleeper section, peripheral detail structure around the voids in the porous basalt aggregate does not have significant changes; no obvious damage occurs around the voids after fatigue loading; and the voids have no effect on the overall mechanical properties of the sleeper.

(a)   Before cyclic loading

(b) After 2 million times of cyclic loading

Figure 7 Variation law of deflection of sleeper W4 under stepwise static loading

3.3 Analysis of Crack Growth Under Cyclic Loading

Taking sleeper W1 as an example, the crack growth law on the section of the concrete sleeper with porous basalt coarse aggregate under the rail is analyzed. It can be seen from Fig. 8 that the fatigue crack appears near the center line of the section under rail beneath the loading point. During the period of 10000 to 100000 times of cyclic loading, the crack length growth rate is 3.2913 mm / 10000 times (in the tests, the crack length is the vertical distance from the crack tip to the bottom of the sleeper). During the period from 100000 to 2 million times of cyclic loading, the crack length growth rate is close to 0 mm / 10000 times. During the loading process, the fatigue crack growth rate of the sleeper shows a continuous and uniform variation, with no sudden change caused due to the existence of voids in the basalt aggregate. The distance between the lowest prestressed reinforcing steel of the new II type sleeper and the bottom of the sleeper is 43 mm. After 100000 times of cyclic loading, the crack length basically remains at about 43 mm. As analyzed, during the first 100000 times of cyclic loading, the concrete in the protective layer cracks first and at a growth rapid rate since the concrete at the bottom of the section under rail suffers tensile stress. Until the crack reaches down to the lowest prestressed reinforcing steel, the crack length growth rate reduces due to the restraining effect of the prestressed reinforcing steel.

And the crack almost no longer propagates after 100000 times of cyclic loading. This shows that the crack growth rate of the sleeper has a relation to the height of the prestressed reinforcing steel in the sleeper, and no correlation with the voids in the porous basalt aggregate.
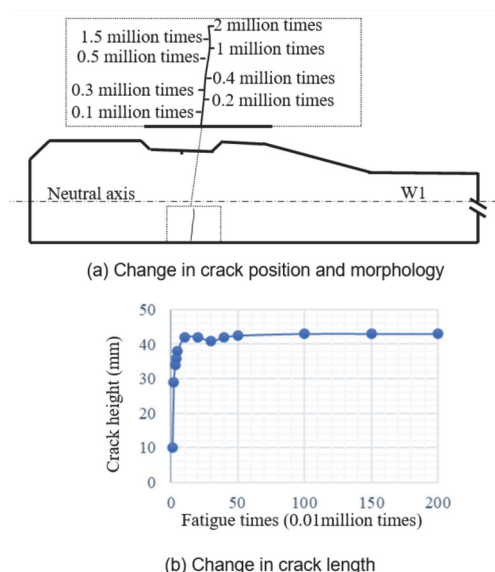

(a) Change in crack position and morphology

(b) Change in crack length

Figure 8 Trend of crack length growth of sleeper W1 under rail

Sleeper W3 does not crack after 2 million times of fatigue loading. According to the requirements of TB/T1878-2002, the sleepers W1 and W2 with cracks are loaded 2 million times and then return to unloading state. Their crack width is then measured with the crack width gauge within 5 min. Their maximum residual crack width is both less than 0.05 mm, which meets the requirements as specified.

The variation trend of crack length on the middle section of W4 sleeper during cyclic loading is shown in Fig. 9. It can be seen from the figure that the fatigue crack appears near the center line of the mid-sleeper section beneath the loading point. During the first 200000 times of cyclic loading, the concrete in the protective layer cracks first and at a rapid growth rate since the concrete at the bottom of the section under rail suffers tensile stress. During the period from 200000 to 400000 times of cyclic loading, the rate of growth upward from the height of the lowest row of prestressed reinforcing steel gets slower due to the tension of the prestressed reinforcing steel. In the stage of 400000 to 500000 times of cyclic loading, after the tension of prestressed reinforcing steel is overcame, the crack growth rate slightly increases until 1 million cycles, when it keeps stable, and the final crack length of the fatigue tests is less than the height of the neutral axis. During the growth process, the crack length growth rate shows a continuous and uniform variation, with no sudden change caused due to the existence of voids in the basalt aggregate; the crack growth rate and crack length are mainly related to the height of the prestressed reinforcing steel and the height of the neutral axis, irrelevant to the voids in the porous basalt aggregate.

The sleepers W4, W5, and W6 are loaded 2 million times and then return to unloading state. Their crack width is then measured with the crack width gauge within 5 min.

Their maximum residual crack width is all less than 0.05 mm, which meets the requirements as specified.
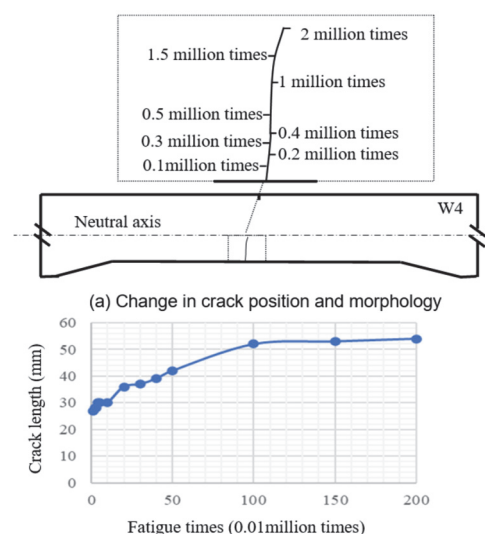

(a) Change in crack position and morphology

Figure 9 Trend of crack length growth of sleeper W4

4 CONCLUSION

Based on the fatigue tests of six concrete sleepers with porous basalt as the aggregate, the fatigue characteristics of the concrete sleepers with porous basalt as the aggregate are studied, with their local stress, elastic deformation and crack growth analyzed, to explore the performance of the sleepers. The following conclusions are obtained:

(1) During the process of 2×10^6 times of loading on the concrete sleepers with porous basalt as the aggregate, the sleeper strain-load relation has no change; the sleeper deformation and stress show a linear relation, with no significant sudden stress caused due to the existence of voids in the aggregate.

(2) The deflection of the sleepers increases as cracks occur, but load and deflection basically maintain a linear relation without change. This indicates no obvious damage around voids in the porous basalt aggregate, and no effect of voids on the overall mechanical properties of the sleepers. After 2 million times of cyclic loading, the sleepers can maintain the original elasticity, and its carrying capacity will basically not decrease.

(3) Under the repetitive fatigue cyclic loading, the fatigue crack growth rate of the sleepers does not change abruptly. It is related to the height of the prestressed reinforcing steel and irrelevant to the voids in the porous basalt aggregate. The final residual crack width is less than the standard value as specified.

As the research shows, the concrete sleepers with porous basalt as the aggregate has a fatigue carrying capacity that meets the requirements for use. Therefore, From the point of view of mechanical properties, they can be further promoted in the construction of the Mombasa-Nairobi Railway and the Nairobi-Malaba Railway in Kenya.

At the same time, the author speculates that porous basalt aggregates can also be used for transportation infrastructure such as bridges, tunnels, and pavement projects, but this requires further research.

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