TWENTY YEAR'S EXPERIENCE ON SLAB TRACK

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INTRODUCTION

Twenty years have passed since slab track was put into practical use by the former Japanese National Railways (JNR). Slab track has been laid both on Shinkansen and narrow gauge lines for over 2400 km including the Seikan under-sea tunnel and Honshu-Shikoku over-sea bridges where the natural environment is very severe. The slab track has come to be considered indispensable for the Shinkansen, and was adopted for about 1300km on Tohoku and Joetsu Shinkansen lines which is equivalent to 90% of these lines.

In the past twenty years, slab track has brought on a great change in the maintenance of railroad track, especially on the Shinkansen lines. This is because of its excellent performance in maintaining good track geometries and in reducing the maintenance costs of track. This is quite obvious when comparing slab tracks with ballasted tracks in each Shinkansen line. It has even changed the system of maintenance.

This paper describes the economic and technical effects of slab track, its technical background based on the twenty year's experience, the present condition of slab track, and the latest research and development on slab track.

1. CIRCUMSTANCES OF DEVELOPMENT

Ballasted track has some strong points: construction costs are low, it is easy to repair track irregularities and so on. However, in recent years, the destructive force to the track has increased with the increase in the number of trains and the rise of train speed, therefore more labor and expenditure are needed to maintain the track in good condition. The volume of maintenance work relating to ballast constitutes the largest part in the entire track maintenance work and its share is approximately 40%. Accordingly, making the track structure ballast-less is effective for the development of a labor saving track.

The first attempt to develop a ballast-less track started around 1930 [1][2]. JNR had adopted a direct-fastened track structure with buried wooden or concrete blocks in a concrete roadbed in Fukasaka Tunnel in 1957 and Hokuriku Tunnel in 1962 [3]. This execution marked the initiation of labor saving track structure in JNR, but this structure was not a great success.

At the time of constructing the Tokaido Shinkansen Line in 1960, various studies were made concerning tracks capable of withstanding a speed of 210km/h. However, in those days, there was no means other than the ballasted track structure [3] because of uncertain knowledge about the track deterioration due to high speed operation and about the appropriate track maintenance method about unconventional tracks [4].

With the opening of Tokaido Shinkansen Line in 1964 and the establishment of a nationwide Shinkansen network project, JNR organized a committee on the new track structure in 1965 and started an earnest study of this subject. This track structure was energetically promoted through theoretical analysis, indoor experimentation, trial track laying on the existing lines and so on. The targets of the development at that time were [2]:

(1) The construction cost should not exceed twice as much as ballasted track.
(2) The track should have enough strength for train running, and the resilience of track structure should be at least equivalent to that of ballasted track.
(3) The construction speed should not be less than 200m per day.
(4) The adjusting capability of track irregularities against the deformation of the substructure should be not less than 50mm for vertical direction and ±10mm for lateral direction.

After repeated studies, some track structures which met these targets were proposed. They are as follows:

(1) Slab Track type A (concrete slab type track using cement–asphalt mortar)
(2) Slab Track type M (concrete slab type track with adjustable mat)
(3) Slab Track type L (concrete slab type track using long tubes with grouted cement)
(4) Slab Track type RA (concrete slab type track on roadbed)

As a result of repeated performance tests and laying tests in the Railway Technical Research Institute and on some existing lines, Slab Track type A was finally selected as a standard track structure for Shinkansen in view of its economic advantage, construction speed and so on. At the time of constructing the Sanyo Shinkansen line between Osaka and Okayama in 1970, the track was laid on 16km sections in tunnels and on viaducts (5% of the total length). For the Sanyo Shinkansen line between Okayama and Hakata covering the trackage of 782km completed in 1974, 69% of the total length was constructed using slab track. For Tohoku and Joetsu Shinkansen lines having the trackage of 1470km, approximately 90% of the total length was constructed with slab track (including resilient tie track on concrete bed filled with concrete)(Cf. Table 1).

Table.1 Extension of slab and ballast tracks by sturucture

Structure	Tokaido Shinkansen (Tokyo – Shin-Osaka)		Sanyo Shinkansen (Shin-Osaka – Okayama)				Sanyo Shinkansen (Okayama – Hakata)				Tohoku Shinkansen (Omiya – Morioka)				Joetsu Shinkansen (Omiya – Niigata)			
	Extension (km) Ballast	Ratio (%)	Track (km)		Extension (km)	Ratio (%)	Track (km)		Extension (km)	Ratio (%)	Track (km)		Extension (km)	Ratio (%)	Track (km)		Extension (km)	Ratio (%)
			Ballast	Slab			Ballast	Slab			Ballast	Slab			Ballast	Slab		
Soil work	274	54	12	0	12	7	54	4	58	15	3	23	26	5	1	2	3	1
Bridge	57	11	20	0	20	12	16	15	31	7	4	70	74	16	4	27	31	11
Viaduct	116	22	71	3	74	45	45	41	86	22	39	219	258	55	14	121	135	49
Tunnel	69	13	53	5	58	35	10	213	223	56	1	111	112	24	0	106	106	39
Total	516	100	156 (95%)	8 (5%)	164	100	125 (31%)	273 (69%)	398	100	47 (10%)	423 (90%)	470	100	19 (7%)	256 (93%)	275	100

2. DETAILS OF SLAB TRACK TYPE A

2.1. Track structures[3][4]

Typical types of track slab structure for the Shinkansen are shown in Fig. 1(1) for open sections and in Fig.1(2) for tunnel sections.

The slab track consists of precast concrete slabs 5m long and Cement Asphalt–

Mortar(CAM) layer beneath the slab. On the roadbed concrete of a viaduct or in a tunnel, lateral stopper concrete (400 mm in diameter and 200mm high) is provided at intervals of 5m. This lateral stopper concrete serves to prevent the track slab from moving in both longitudinal and lateral directions.

The track slabs are made of pre-fabricated RC(Reinforced Concrete) or PC (Pre-stressed Concrete) or PRC(Pre-stressed Reinforced Concrete). The track slab for the Shinkansen is 2340mm wide, 4930-4950mm long and 160-200mm thick. One track slab weighs approximately 5 tons.

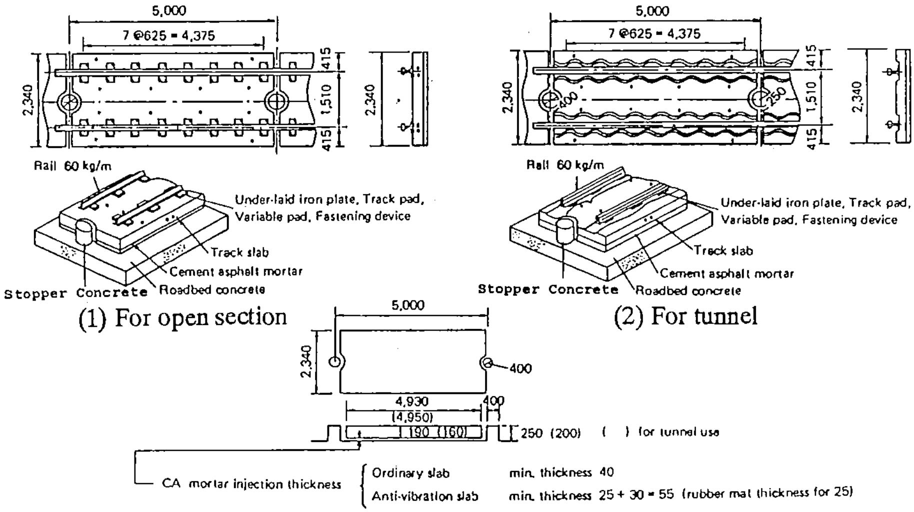

Fig.1 Slab Track

2.2. Characteristics of track slab[4]

Several types of track slab selected depending on the location are shown in Table 2. The meanings of the symbols used in their naming are shown in Fig. 2.

Table.2 Applications of Tohoku and Joetsu Shinkansen track slabs

Location			Structure		Shape and size (mm) Length	Width	Thickness	Cut radius	Rein-forcing bar coverage	Protrusion size (mm) Radius	Height	Note
Ordinary slab	Open section	Warm area	RC	A-55M	4,930	2,340	190	280	20	200	250	Slab mat A-T-43- New used
		Cold area	PRC	A-55C	4,930	2,340	190	280	30	200	250	
	Tunnel section	Straight track	RC	A-51C	4,950	2,340	*200	250	30	200	200	
		Curved track and section 200 m from tunnel inlet	RC	A-55CT	4,950	2,340	160	280	30	200	200	See Note 2
Vibration-deadening slab	Warm area		RC	A-55MN	4,930	2,340	190	280	20	200	250	Slab mat A-30-24 A-T-43- New used
	Cold area		PRC	A-55CN	4,930	2,340	190	280	30	200	250	

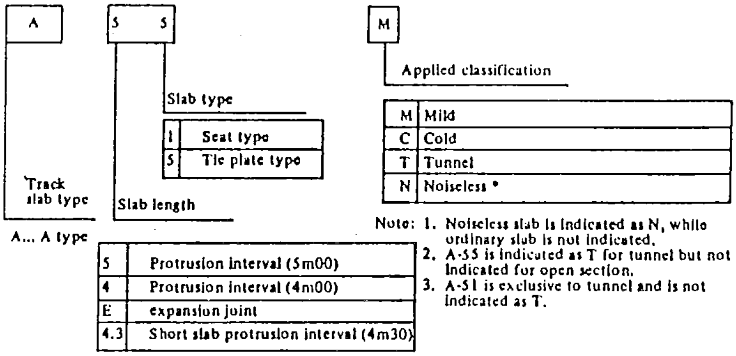

Fig.2 Signs of structure type

2.3. Structural analysis of slab track

In the early stages, the vertical deformation of slab track was due to wheel load and had been analyzed using the double–layer–beam–model on continuous elastic foundation[1]. The track slab for the Sanyo Shinkansen was designed based on this. However, in the development of the slab track for the Tohoku and Joetsu Shinkansen, calculations were done by FEM–model shown in Fig.3[5], since the actual rails were elastically supported on the track slab at certain intervals, and the track slab was not a beam, but a plate.

2.4. Laying of slab track[4]

At the construction site, the roadbed concrete is placed to a predetermined height. At the track center, concrete stoppers are mounted at every 5m. It also serves as a reference point for setting track slab. After adjusting the position, the four corners are fixed by holding bolts. A clearance of about 50mm is provided between the bottom of the track slab and the surface of the roadbed concrete. Mixed CAM is injected into this clearance and around the stopper. Then the rail fasteners sre fitted to the track slab and the rails are fastened. The rail surface is made smooth by the adjust packing. The tolerances of slab finishing are shown in Table 3.

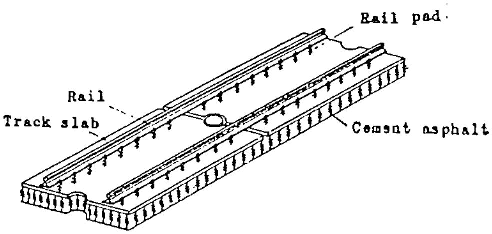

Fig.3 Model for the stress–analysis of the track slab

Table.3 Finishing limit

	Finishing limit
Track gauge	+ 1, − 2 mm
Cross-level	± 1
Longitudinal level	± 2 (10 m length)
Alignment	± 2 (")

3. PRACTICAL USE OF TRACK SLAB ON TOHOKU AND JOETSU SHINKANSEN

3.1. Differences between Sanyo Shinkansen and Tohoku Shinkansen[6]

It was learly confirmed that slab track had good qualities as a labor-saving track. However, there were still some points to be improved before the construction of the Tohoku Shinkansen, for example; the noise produced from a running train is higher in the case of ballasted track, CAM used in warm climate is weak under freezing and thawing conditions, and so on. The differences between the track slabs of the Tohoku Shinkansen and those of the Sanyo Shinkansen are as follows. Main point is that the former is constructed upon a cold-resistant design concept for use in cold areas and some important improvements were made based on the experience from the Sanyo Shinkansen.

(1) In order to solve the noise problem which was a weak point of the slab track, the vibration-reducing slab track was laid.
(2) The CAM type-AE for cold areas which is resistant to damage was developed. Uniform bubbles are formed at regular intervals in the CAM to reduce damage due to melting.
(3) The PRC slab is used in cold areas to avoid cracks on slab surface and resulting water penetration which brings about a freezing ice damage.
(4) The slab thickness for open sections was increased from 16cm to 19cm.
(5) In cold areas, more than 10cm thick roadbed concrete is placed on the viaduct slab to avoid water penetration into CAM.
(6) Newly developed rail fastening (type 8 i.e. improved type 5) was used. The main springs of the direct-fastening device type 5 which are used for the slab track A-55 tended to loosen and drop off with train operation, so that 30% of the slab maintenance cost was spent for the fastening maintenance in the Sanyo Shinkansen.
(7) The semicircular concrete stoppers which are used at the end of structures were reinforced. They were sometimes damaged, when they were situated at the end of the PC bridge or around the expansion joints for long rail. Therefore, the semicircular stopper was protected by a steel frame, a rubber piece was attached to the end of the track slab to protect the CAM and the steel plate was replaced with stainless steel to decrease the friction.
(8) RA slab track on a soil roadbed was experimentally laid in the Joestu Shinkansen line[6].

3.2. Development of vibration-reducing slab track

An important problem for JNR (or even for JR now) has been how to harmonize "high speed" and "human living environment". Efforts have been made to comply with the noise standards specified in "the Environment Standards Concerning Shinkansen Railway Noises (Japanese Environmental Agency Notification No.46 of July, in 1975)"[7].

According to early tests on the Sanyo-Shinkansen, it was proved that the noise level on slab track was about 5dB(A) higher than on ballasted track. When the study of noise levels began in the early 1970's, there were still many unknown factors concerning noise and vibration. However , it was suggested by an analysis that increasing the resiliency of slab supporting material is effective to reduce noise and vibration[8].

Various types of vibration-reducing slab tracks were tested. Fig. 4 shows the structure of Vibration A-type Track Slab (henceforth VA-Slab) with the rubber slab mat held between the CAM layer and the track slab in order to improve the supporting elasticity[7]. As compared with the Sanyo Shinkansen where VA-Slab track account for 5% of the total extension of slab track, the Tohoku Shinkansen uses them over the extension of about 30%.

In 1974 a performance test of the VA-Slab track was carried out on the Sanyo Shinkansen to confirm the noise-reducing effect of it. The spring constant of the rubber slab mat was 4.3MN/m for a test piece (10cmx10cmx2.5cm thick). As a result, the track resulted in a noise reduction of only 1dB(A) when compared to that of ordinary slab track. At the next stage, new VA-Slab track with rubber slab mats, whose spring constant was 2.4MN/m, was tested on the Oyama Test Line of the Tohoku Shinkansen which was already completed. According to the frequency analysis on the VA-Slab track and the ordinary slab track, the reduction in each frequency on vibration acceleration level from the rail to the viaduct is shown in Fig. 5. The level reduction of the VA-slab track was smaller than that of the ordinary track in the 100 to 250Hz range but it was greater than 10dB in the 1000 to 2000Hz range[9].

On the other hand, according to the data of viaduct vibration- velocity-level corrected by sense of hearing, the noise-reducing effect of VA-slab was 3dB(A) as compared with ordinary slab track[8]. It was especially effective in reducing the noise level in the high frequency domain. As stated above, the VA-slab played a major part in solving the noise problem of the Tohoku and Joetsu Shinkansen. The result of a series of tests showed that noise caused by a running train would be attenuated by reducing the spring constant of the slab track, but the reduction of its spring constant was smaller than the value expected because of the shape effect of slab rubber mat: Its plane shape prevents the effective value of the supporting elasticity from being reduced as much as expected[10].

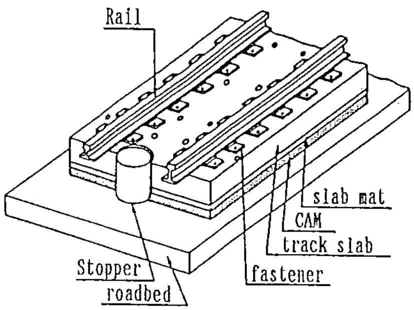

Fig.4 Vibration-Reducing A-type Track

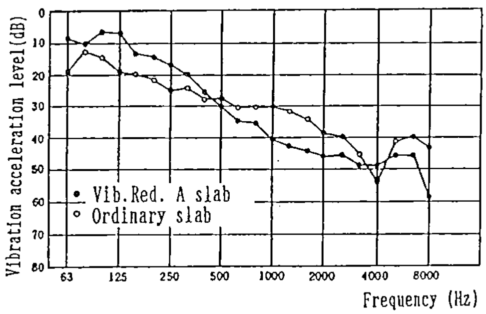

Fig.5 Reduction from rail to viaduct (vibration acceleration level)

Technical development has been undertaken with a view to increasing the free surface of the rubber mat, which allows comparatively large deformation under train passage. Vibration-Reducing G-type Track Slabs (henceforth VG-Slab) whose grooved slab mat was glued leaving a void (soft middle plate) in the central part was introduced (Cf.Fig.6). In the train running test(210km/h) on the Kitakami section of the Tohoku Shinkansen, VG–Slab resulted in a noise reduction of 5dB(A) over that of the VA–Slab measured on the ground under the viaduct (Cf.Table 4)[11].

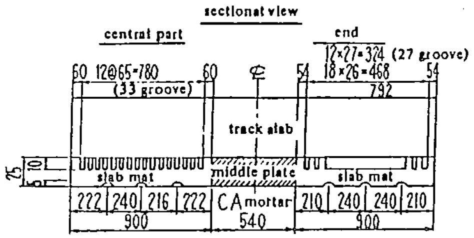

Fig.6 Vibration–Reducing G–type Track

Table.4 Difference between VG–Slab and VA–Slab on noise level (VA–slab)–(VG–slab)

Measuring points	difference
Above the floor slab	-1 dB(A)
Under the floor slab by 0.3m	3 dB(A)
Under the viaduct, 1.2m high on the ground	5 dB(A)
25m out of the viaduct, 1.2m high on the ground	1 dB(A)

-:increment, train speed =210km/h

3.3. Development of CAM for cold climate[12]

One type of CAM for mild climate(henceforth No.8) did not endure freezing and thawing in laying tests in cold climate. Thus it was pointed out that its quality would have to be improved, if it was to be used in a cold climate. CAM–No.8 had the following problems when applied in a cold climate.

(1) Damage to the CAM layer such as cracks, scaling and so on, after being exposed to the cold air for several years in Hokkaido or Nagano.

(2) The strength of the CAM layer and its modulus of elasticity at low temperature increased and the quality of CAM became brittle.

(3) Construction work in the cold season required heavy facilities for keeping materials warm and for heat–curing the CAM.

(4) According to experience, the poor conditions of execution, load action and weathering had caused cracking and scaling of the CAM.

As the CAM is a composite material containing much water and receiving external water such as melting snow and rain, the damage (by frost) of CAM may be explained by the Hydraulic Pressure Theory. In this theory, materials like cement concrete are damaged by movable water pressure, caused by water being converted into ice. Thus, the following will be effective steps :

(1) To decrease the water content by improving asphalt emulsion and reducing the quantity of sand.

(2) To make the quality of CAM dense and water–proof by applying an anti–foaming agent and polymer.

(3) To introduce bubbles into CAM layer to relax the pressure by applying an air–entraining–agent.

Following the above considerations, the tests were carried out over several years in which dozens of combinations brought forth an economically compatible CAM with high durability factors such as workability, strength, fatigue resistance, elasticity, thermal sensitivity, freezing–thawing resistance, weatherability, etc. Fig. 7 shows the resistance of CAM against freezing–thawing. In this the relative dynamic elastic coefficient means the ratio of dynamic elasticity to static one. From these results, the standard ingredient of CAM for cold climates (No.33) was formulated as shown in Table 5.

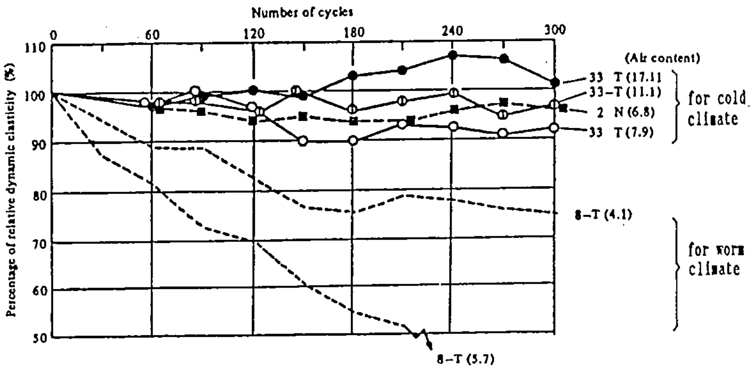

Fig.7 Resistance of CAM against freezing-thawing

Table.5 Ingredient of CAM for cold climate

(Unit: kg/m^3)

High early strength cement	Admixture	Asphalt emulsion	Fine aggregate	Water	Aluminium powder	Antifoaming agent	Air-entraining agent
255	45	480	600	under 105	0.04	0.15	7.5

3.4. Development of PRC track slab[13]

The Tohoku and Joetsu Shinkansen lines are situated at 36 degree to 40 degree North Latitude, in areas which have a lot of snow in the winter. The section between Echigo-Yuzawa and Nagaoka has snowfall exceeding 3 meters. To keep the train operation at 210km/h in this section, the water sprinkler snow-melting system was adopted for 76km of section on the Joetsu Shinkansen line. Especially in these areas water will penetrate into track slab, if cracks develop on its surface. That is why the PRC structure is used in cold areas. The main points which were considered in the designing of PRC track slab were as follows.

(1) This slab was designed to bear two 17 ton axles, 2.5m apart on one slab, with a dynamic increment of 1.45 normally (wheel load taking fatigue into consideration [fatigue load] is 122kN) and 3.0 exceptionally (wheel load taking wheel flat into consideration [design load] is 250kN).
(2) Under fatigue loads, tensile stresses would not occur on the surface of the slab.
(3) Under design loads, cracks would not exceed 0.1mm wide.

To control the crack width in designing the slab, it was necessary to clear up the relationship between reinforcement-bar stress and crack width. Fig.8 shows the results of some loading tests for slabs. It is seen that if the reinforcement-bar allowable stress is 100 MPa, the crack width will be smaller than 0.1 mm. Other dynamic repeated load tests were carried out to clear up the relationship between the number of repeated loadings and permanent cracks. The results showed that if the stress of reinforcing-bar is under 100 MPa, the permanent crack width will be smaller than 0.1mm wide even after 2 million times of loading. As a result, the design method (partly adopting a limit state design method) for PRC track slab was established, and PRC slab was used on open sections in the north of Utsunomiya on the Tohoku Shinkansen line and north of Kanasima on the Joetsu Shinkansen.

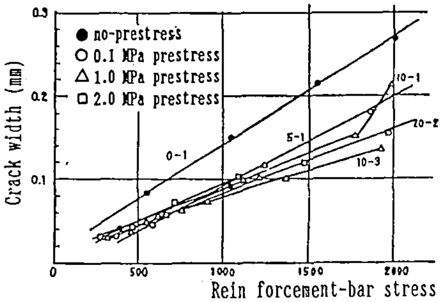

Fig.8 Relation between reinforcement-bar and crack midth

4. PRESENT CONDITION OF THE SLAB TRACKS

4.1. The passing tonnage and track condition

Fig.9 shows the Shinkansen load tonnage up to 1990. In recent years, this figure has been gradually increasing. The latest track conditions are shown in the form of irregularities found per km in Fig.10. This means the number of irregular points (per km) which exceeds the target value for riding control for the Shinkansen. Thus the slab track keeps the track in better condition than ballasted track.

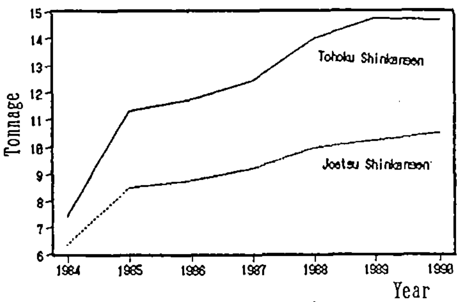

Fig.9 Annual gross tonnage (million gross tons)

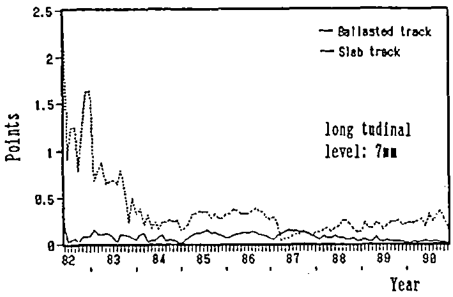

Fig.10 Histry of track irregularities (Out-of-limit points/km)

4.2. Problems on the Tohoku and Joestu Shinkansen lines

There is no fatal problem in track maintenance on the Tohoku and Joestu Shinkansen lines, because the tracks were constructed by referring to the experience of the Sanyo Shinkansen. However, after the lines were opened for service, we did find some problems:

(1) Damage to CAM injected around concrete stoppers near expansion joints (because of strong longitudinal forces)
(2) Damage to CAM layer such as cracks, peeling off and so on in cold climate (because of coldness and snow)
(3) Cracks on the track slab surface (because of alkali–aggregate reaction)
(4) Occurrence of irregularities in the longitudinal level of a wave length almost equal to the girder span (because of the contraction and creepage of drying concrete of RC and PC girders)
(5) Occurrence of irregularities in the longitudinal level in tunnels (because of swollen invert concrete)
(6) Warping of track slabs in tunnels (because of variation of humidity)
(7) Damage to insulating collars (because of inadequate component quality or retightening)
(8) Decrease of anti–rust protection oil in insert collars.

In order to solve these problems, various countermeasures have been adopted. Henceforth, it is important for us to develop a more economical repair method.

4.3. Maintenance costs of slab track

Fig.11 shows the slab track maintenance costs of Shinkansen lines. The costs of the Sanyo Shinkansen line tends to increase after 1975 when the track was opened for service, but there is not very much change except in 1983 to 1984. This figure shows that the costs on fasteners and lining are on the decrease. On the other hand, the costs of Tohoku Shinkansen line have increased since 1982 when the track was opened for service. This figure shows that the costs of leveling are decreasing, but the costs of repairing on CAM layer are increasing rapidly. The costs of repairing on CAM layer and fasteners of the Tohoku Shinkansen line are higher than those of the Sanyo Shinkansen.

Fig.12 shows the ratio of maintenance costs of the slab track versus the ballasted track. The ratio for the Sanyo Shinkansen line averages 0.18 over 16 years, and that of the Tohoku is 0.33 over 9 years. This is because the maintenance costs of ballasted track have been decreasing since 1987 when the JNR was separated into several companies. (The new JR Firms took a new look at track maintenance in consideration of management.)

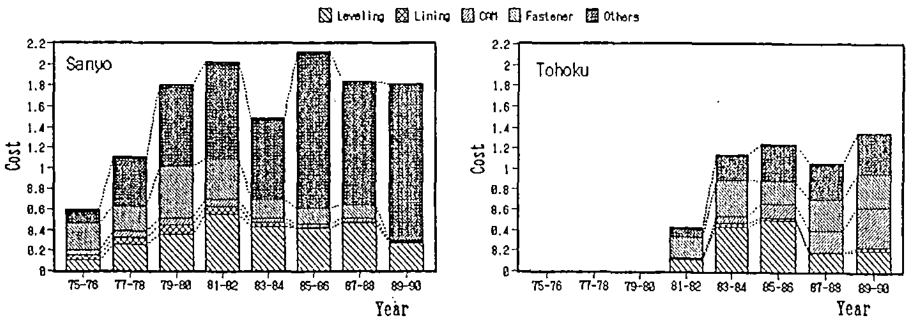

Fig.11 Histry of track maintenance costs (million yen/year/km)

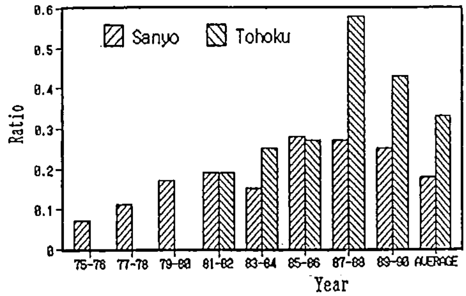

Fig.12 Ratio of maintenance cost of slab track to ballasted track

5. LATEST RESEARCH AND DEVELOPMENT ON SLAB TRACK

5.1. Reduction of construction cost

The construction costs of slab track are 1.3 to 1.5 times those of ballasted track. Thus the first target in development of slab track as described in chapter1 has been achieved sufficiently. In this case, if the passing tonnage is about 12 million tons in a year, it is likely that the difference in initial costs (the construction costs) between the slab track and the ballasted track will be recovered in ten years. Also, in view of the total construction costs of elevated tracks, slab tracks stand at an advantage due to the difference in dead load on the floor slab bed. Generally, with respect to elevated tracks and tunnels, slab track is superior to ballasted track, even when construction and maintenance costs are taken into account.

However, considering the Shinkansen network project such as the Hokuriku Shinkansen line, further reduction of construction costs has been desirable. One of the countermeasures is the use of frame-shaped slab track as shown in Fig.13.

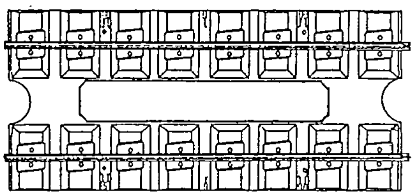

Fig.13 Frame-shaped slab track

5.2. Environmental preservation

Japanese Railway Companies are planning to increase the train speed on Shinkansen lines. Several countermeasures as follows are being considered:

(1) Countermeasure for wheel/rail noise (rolling noise) such as the use of sound-absorptive material on the surface of the track slab, rail grinding and so on.

(2) Countermeasures for structure-borne noise and ground vibration such as a highly resilient tie pad, new types of slab track (with elastic sleepers) and so on.

6. CONCLUDING REMARK

Twenty years of experience using slab track on the Tohoku and Joetsu Shinkansen is presented above. The fact that the slab track accounts for more than 90% of these lines indicates that a long-cherished dream of maintenance-free operation has been substantially realized. Since opening for service, the slab tracks proved their full ability to meet the needs of low maintenance, labor saving, protection from snow and cold and environmental protection.

In the future the construction of the Shinkansen-network will encounter the problem of how to reduce costs in addition to the above factors. Continuous efforts in technical development will be required to meet the various demands while reducing costs at the same time.

References:

[1] Yutaka SATOH: Development of New Rail Track Structure, Quarterly Reports RTRI (Railway Technical search Institute in JNR or JR), Vol.10, No.2,1969, p.62-p.70.
[2] Kainen WATANABE: Labor Saving Structure and Modernized Maintenance System of Track,Permanent Way,No.89,1982,p.3-p.31.
[3] Shigemi TANI,Labor Saving Track Structure of JNR,Japanese Railway Engineering, No.94,June,1985.p.12-p15.
[4] Hankichi UZUKA: Prestressed Concrete Sleepers and Track Slab of JNR,Japanese Railway Engineering,Vol.24,No.3,1984,p.6-p.10.
[5] Tsunehiko SAITOH: tress Analysis of Concrete Track Slab on an Elastic Founda tion by the Finite Element Method, Quarterly Reports RTRI, Vol.15,No.4,1974, p.186-p.196
[6] Katsutoshi ANDO:Study on Pavement of Concrete Slab Track laid on Sub grade, Quarterly Reports RTRI,Vol.23,No.1,1982,p.12-p.15.
[7] Isohiro TANAKA,Toshihiro SHIDOJI: Track Construction of Tohoku Shinkansen, Permanent Way,Vol.91,1982,p.4-p.15.
[8] Yoshihiko SATOH: Recent Developments in Railway Track Mechanics in JNR, Japanese Railway Engineering,Vol.20,No.4,1981,p.14-p.18.
[9] Kainen WATANABE: The Problems in Application of Slab Track to Tohoku and Joetsu Shinkansen and Their Solutions(in Japanese), Proceedings of Japan Society of Civil Engineers,No.385(VI-7),Sep.1987,p.128-p.133.
[10] Kainen WATANEBE: Technical Development of the Labor-saving Type Track Structures, Quarterly Reports RTRI,Vol.22,No.4,1981,p.145-p.152.
[11] Yoshihiko SATOH,Hujio OHISHI,Satoru KOBAYASHI: Development of Vibration reducing G-Type Slab Track,Railway Track(in Japanese), Vol.30, No.3, 1982,p.143-p.146.
[12] Yutaka HARADA,Seiichi TOTTORI, Noriyuki ITAI,Takaharu NOTO:Development of Cement-asphalt Mortar for Slab Track in Cold Climate, Quarterly Reports RIRI, Vol.24,No.2,1983,p.62-p.67.
[13] Y.TERASIMA: Design on Track Slab for Tohoku Shinkansen, Structure Design Office Note, No.51, 1977.9, P.20-P.25.