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Comparative Investigations into Environment-Friendly Production Methods for Railway Prestressed Concrete Sleepers and Bearers

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Abstract: Prestressed concrete sleeper is a safety-critical track component widely used in ballasted railway tracks. The performance, endurance and quality of prestressed concrete sleepers can detrimentally affect the serviceability and durability of a railway track. An optimal production method is an important criterion underpinning quality and durability over the entire service life of prestressed concrete sleepers. At present, the research work of the sleeper mainly focuses on the dynamic load, bearing capacity and structural design method, etc. However, there exists a lack of research on the specific advantages and disadvantages of the sleeper production process and the improvement of the sleeper process research. This study is the world's first to collect and analyse the technical data and characteristics of modern production methods of prestressed concrete sleepers, including the long-line system method, pre-tensioned long-mould flow method, pre-tensioned short-mould flow method, post-tensioned short-mould flow method and instant-demoulded short-mould flow method. The precautions for these prestressed concrete sleepers are highlighted in the paper as well. The research results show that the long-line system method, pre-tensioned short-mould flow method, post-tensioned short-mould flow method and instant-demoulded short-mould flow method have a higher automation level and lower efficiency than the pre-tensioned long-mould flow method. The production method of the pre-tensioned long-mould flow method has high efficiency and low cost of equipment, but more workers are needed. Through a comparative analysis, this paper also determines the environmental impacts and provide new references and suggestions for the development and progress of sleeper production technologies.

Keywords: prestressed concrete sleeper; production method; long-line system; mould flow method

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1. Introduction

Railway sleepers are one of the key components in ballasted railway tracks. A main function is to bear the loads from the rails in all directions and transfer on to the ballast bed [1–3]. At the same time, railway sleepers help maintain the geometry of a rail track such as rail gauge and track alignments [4,5]. Based on their shape and dimension, railway sleepers can be classified as monoblock sleepers [6], twin-block sleepers, ladder-shaped sleepers and Y-shaped sleepers. The sleepers can be manufactured using different materials such as wooden sleepers, concrete sleepers, steel sleepers and composite sleepers [7,8]. The sleepers can be designed to provide different directions supporting rails, including transverse sleepers, longitudinal sleepers and short sleepers [9,10]. In addition, the sleepers can also be referred to differently based on their applications such as track sleepers, bridge transom sleepers and turnout bearers, etc. [11]. All these different types of sleepers are shown in Figure 1, respectively.

(**a**) (**b**)

(**c**) (**d**)

(**e**) (**f**)

Figure 1. *Cont.*

(**g**)

(**h**)

(**i**)

(**j**)

(**k**)

Figure 1. Different type of sleepers: (**a**) twin-block sleepers; (**b**) monoblock sleepers (concrete sleepers); (**c**) ladder-shaped sleepers; (**d**) Y-shaped sleepers; (**e**) wooden sleepers; (**f**) steel sleepers; (**g**) composite sleepers; (**h**) longitudinal sleepers; (**i**) short sleepers; (**j**) bridge transom sleepers; (**k**) turnout bearers.

At present, a majority of ballasted railway tracks around the world mainly adopt monoblock prestressed concrete sleepers, which are manufactured with high strength, high stability and durability [12]. At present, about 500 million concrete sleepers are needed every year in railway networks globally [13]. In addition to the common use of wooden sleepers in North America due to the abundance of timber resources [14], concrete has become the preferred material for manufacturing railway sleepers in most other countries around the world [15,16].

For monoblock prestressed concrete sleepers, a large amount of research work has been carried out, which mainly focuses on the dynamic load [14,17], bearing capacity [18,19] and structural design method [20], etc. There exists a lack of research on the specific advantages and disadvantages of the sleeper production method and the improvement research of the sleeper production method. According to the current monoblock prestressed concrete sleepers' state, the major defects of the life cycle of sleepers could be categorized as defects during operation or maintenance, defects during shipping and installation and defects during manufacture. Improper quality control in manufacturing will lead to concrete sleepers' longitudinal crack, muscle crack, head zone crack, decay, tearing and filled plugs. It is important to improve the design and manufacture of concrete sleepers in order to reduce the defects and damages of concrete sleepers [21].

The aim of this research work is to fulfil the gap of monoblock prestressed concrete sleepers' design and production. This paper will evaluate the technical characteristics of concrete sleeper production methods including the long line system method, pre-tensioned long-mould flow method, pre-tensioned short-mould flow method, post-tensioned short-mould flow method and instant-demoulded short-mould flow method. The study also highlights the precautions for these prestressed concrete sleepers [22,23]. Through comparative analysis, this paper identifies new insights into greener production methods for railway concrete sleepers and provides new references and suggestions for the development and progress of the sleeper production technologies.

2. State-Of-The-Art Production Methods of Prestressed Concrete Sleepers

Depending on the time and pattern of prestressing forces transmitting, there are two prestress concepts: pre-tensioning and post-tensioning concepts. Both methods can transmit the prestress to the entire length of the concrete sleeper. The pre-tensioning concept applies initial jacking stress prior to casting concrete, whilst the post-tensioning technique imposes jacking stress after concrete hardening.

Most concrete sleeper production adopts the pre-tensioned method where high-quality control can be achieved. Contemporary sleeper production processes can be divided into two categories: the long-line system method and the mould flow method. For each production process, prestressing force transfer techniques can actually be subdivided into the prestressed steel wire self-anchoring method and the anchorage–anchoring method. It can be noted that the process for the timing of sleeper demoulding can be grouped into (i) after the curing demoulding method and (ii) the instant demoulding method. These sleeper production processes and their classifications are illustrated in Figure 2.

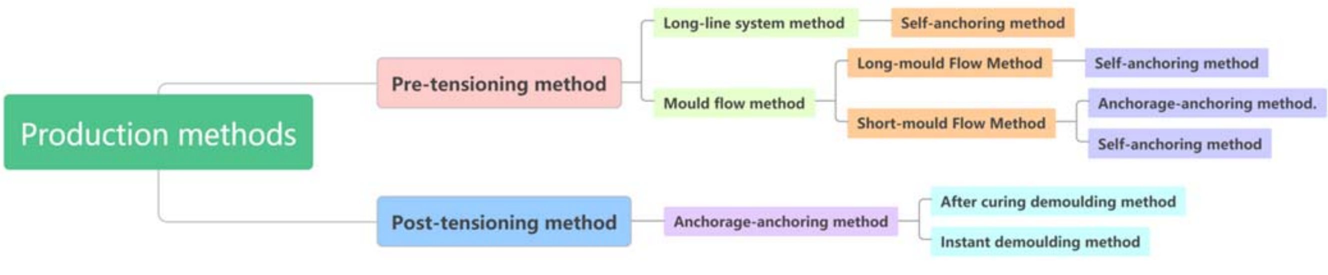

Figure 2. Classifications of sleeper production method.

For the mainly used monoblock prestressed concrete sleepers, assuming the production equipment and technical level of sleeper are common, the technical data and characteristics of modern production methods of prestressed concrete sleepers—including the long-line system method, pre-tensioned long-mould flow method, pre-tensioned short-mould flow method, post-tensioned short-mould flow method and instant-demoulded short-mould flow method—will be collected and analysed below.

3. Long Line System Method

The long-line system method generally refers to the method of manufacturing prestressed concrete members using the pre-tensioned method. In this system, there is a concrete pedestal used to temporarily fix prestressed steel wires and complete the whole process of component production on it. In the process of producing prestressed concrete sleepers by the long-line system method, all or at least part of the prestress is applied to the prestressing wires wire by wire to ensure the uniformity of the prestress between the wires. The prestressed steel wires are usually anchored on the beam at both ends of the pedestal. After the concrete is cured to reach the required strength, the prestress is transferred to the concrete sleepers. Prestressed concrete sleepers produced by the long-line pedestal method usually transfer a prestress between prestressed steel wires and concrete by the friction force between them.

3.1. Process and Technical Characteristics

The production of prestressed concrete sleepers in Australia, Europe, China, the UK and North America mainly adopts the long-line system method. The general length of the concrete pedestal for producing prestressed concrete sleepers is not less than 50 m. The commonly used is 100 m to 120 m, and there are also 200 m of pedestal in some countries to produce prestressed concrete sleepers. The main process of producing prestressed concrete sleepers by the long-line system method is shown in Figure 3.

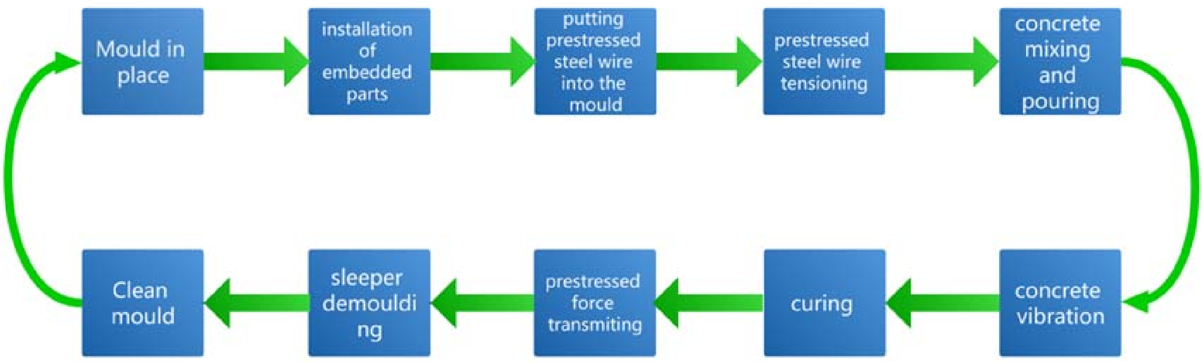

Figure 3. Main process of long-line system method.

For the long-line system sleeper production method, the typical production processes are shown in Figures 4–6.

Figure 4. Overview of long-line system method production plant.

Figure 5. Long-line system method concrete placing.

Figure 6. Long-line system method sleeper demoulding.

The main technical characteristics of the production process of the prestressed concrete sleeper long-line system are shown in Table 1.

Table 1. Technical characteristics of long-line system method.

1	Energy consumption	The mould is fixed in the production process, so it does not need large equipment, and the energy consumption of the production process is relatively low.
2	Labour	The production table position is fixed and the process flow is simple; therefore, less labour was needed—20 workers is enough for a production line.
3	Workshop environment	In the process of vibration compaction, the sleepers generally adopt the mode of plug-in vibration rod and attached vibration equipment, and the vibration noise is low.
4	Production line investment	Since the production equipment cost is not high and the production equipment mobility is good, the production line investment is low.
5	Production efficiency	Because the sleeper and the mould are maintained on the pedestal, the mould cannot be turned around and the production efficiency of the sleeper is low. According to the length of the mould and the number of seats, the daily production of the long-line pedestal method is 500 to 800 sleepers per shift.

3.2. Precautions in Production

The production of prestressed concrete sleepers by the long-line system method has the following points for special attention in the production process:

(a) Since the prestressed steel wire is anchored to the beams at both ends of the pedestal during the tension of the long-line pedestal method, the beams must have sufficient stiffness so that they do not cause the prestressing loss after the tension stressing of the steel wires;

(b) The prestressed steel wires are longer in the long-line pedestal mould and the design of the partition board in the mould should be reasonable; therefore, it does not cause the prestress loss in the process of steel wire tensioning;

(c) Because of the long length of prestressed steel wire and the maintenance on the pedestal, the change of temperature will cause the deformation of steel wires and lead to the difference between the prestress and the design prestress. Therefore, an appropriate temperature should be controlled during the prestressed force transmitting to ensure the prestressed force of steel wires meets the design requirements.

4. Pre-Tensioned Long-Mould Flow Method

The mould flow method, also known as the unit flow method, refers to the production process of concrete products, which are fixed on the workstation by the workers and units who complete each working procedure, and the products move along the process assembly line with the mould. The mould flow method is a type of prestressed concrete sleeper production method commonly used around the world. Based on the length of the sleeper mould, it can be divided into the long-mould flow method and short-mould flow method. The short-mould flow method usually refers to a single sleeper length mould, such as 2 × 1 (sleeper width direction number × sleeper length direction number) or 4 × 1, 5 × 1 mould, etc.

For the long-mould flow method, the prestressed steel wire is usually tensioned first, and the prestressed steel wire is anchored to the mould with a certain frame stiffness. When the concrete is set to sufficient strength, the prestress is transmitted to the sleeper. Because there is more than one sleeper in each row of the moulds, it is not convenient to install an anchorage plate in production; therefore, the prestressed concrete sleepers produced by the long-mould flow method usually transfer prestress between prestressed steel wires and concrete by the friction force between them.

4.1. Process and Technical Characteristics

At present, Australia, Europe, China, Southeast Asia and Russia mainly use the long-mould flow method for the production of prestressed concrete sleepers. The mould of 2×4 or 2×5 is usually used in the long-mould flow method. The main production process is similar to the long-line system method. The main difference is that the sleeper flows with the mould on different stations. The typical technological process is shown in Figure 7.

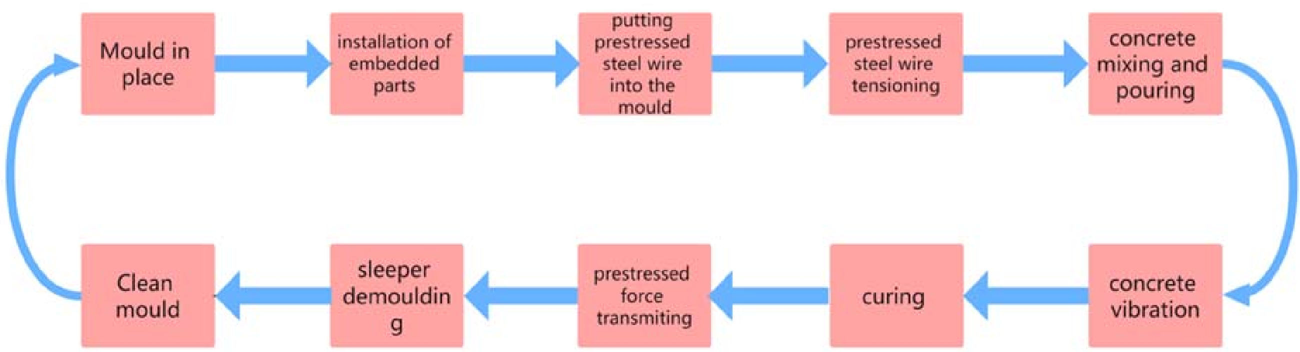

Figure 7. Main process of long-mould flow method.

For the production process of the long-mould flow method, the typical production process is shown in Figures 8–10.

Figure 8. Overview of production line of long-mould flow method.

Figure 9. Long-mould flow method mould and tension process.

Figure 10. Concrete vibration and prestressed force transmitting of long-mould flow method.

The main technical features of the production process of prestressed concrete sleepers are shown in Table 2.

4.2. Precautions in Production

The production of prestressed concrete sleepers by the long-mould flow method has the following issues for special attention in the production process:

(a) Because the prestressing steel wires are anchored to the mould during the process of tension, the mould must have sufficient stiffness and the influence of tension force and self-weight on the deformation of the mould should be considered in order to avoid wire deflection and prestress loss;
(b) For the long-mould flow method, the prestress force of different prestressing wires are applied simultaneously, so the deviation between the material of prestressed steel

wires should be strictly controlled so as to reduce the unevenness of prestress between each individual steel wire;

(c) Due to the repeated circulation and hoisting of the mould in the production process, any deformation may occur, so it is necessary to restrict the detection of the mould in the production process to avoid the fluctuation of the quality of the sleeper product caused by the deformation of the mould.

Table 2. Technical characteristics of long-mould flow method.

1	Energy consumption	In the process of production, the mould flows in a different station and hence needs certain power equipment and hoisting equipment, and the production energy consumption is relatively high.
2	Labour	The process is simple and low automation in production requires a lot of labour—usually, a production line needs about 50 workers.
3	Workshop environment	In order to adapt to the mould flow and set up the process characteristics of the separator in the middle, dry hard concrete is generally used in the long die flow machine method, which leads to the need of large amplitude to dense vibration process, so the vibration noise in the production process is large.
4	Production line investment	The cost of production equipment is not high, so the input cost of the production line is relatively low;
5	Production efficiency	The sleeper mould on the production line has a high flow rate, so the production efficiency is high. The daily production of sleepers is 1000 to 1500 sleepers.
6	Production line versatility	The prestress is usually applied by the method of integral tension and transmitting, so the method could apply to different types of sleepers.

5. Pre-Tensioned Short-Mould Flow Method

The short-mould flow method is a type of mould flow method, usually using a single sleeper length mould (for example 2 × 1, 4 × 1, 5 × 1 mould). Based on the different prestress jacking techniques, the short mode flow machine methods can be classified as the pre-tensioned short-mould flow method and post-tensioned short-mould flow method. The production procedure of the pre-tensioned short-mould flow method is roughly the same as that of the pre-tensioned long-mould flow method. The main difference between the two is the length of the mould. Since the mould length of a single sleeper is convenient for the use of automation equipment, the automation of the production process of the short-mould flow method is higher than that of the long-mould flow method.

5.1. Process and Technical Characteristics

The prestressing steel wires are tensioned along the mould with a certain frame stiffness by the pre-tensioned method, and the prestress is anchored to the sleepers after the concrete has reached sufficient strength. The prestress can be transferred by the friction force between steel wires and concrete or by anchoring plates.

The pre-tensioned short-mould flow method is used in some manufactures of prestressed concrete sleepers in Germany (usually in the form of 4 × 1 or 5 × 1). The main production process is similar to the long-mould flow method. The typical process shown in Figure 11.

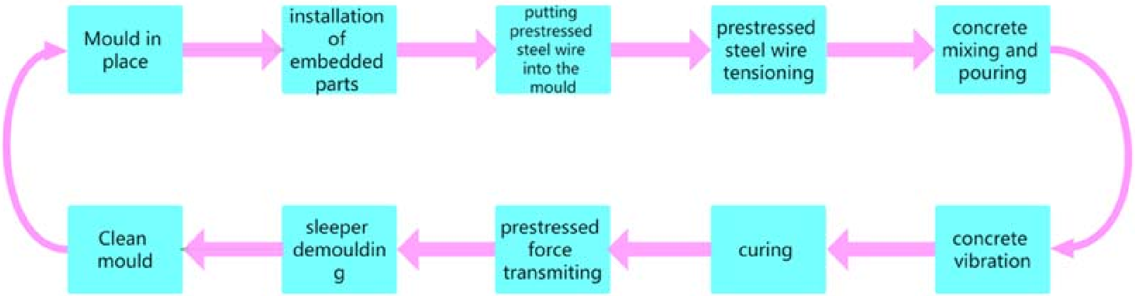

Figure 11. Main process of pre-tensioned short-mould flow method.

The typical production process is shown in Figures 12–14.

Figure 12. Overview of the production line of pre-tensioned short-mould flow method.

Figure 13. Tensioning and concrete pouring of concrete of pre-tensioned short-mould flow method.

Figure 14. Transmitting and demoulding of pre-tensioned short-mould flow method.

The main technical features of the production process of prestressed concrete sleepers are shown in Table 3.

5.2. Precautions in Production

The production of prestressed concrete sleepers by the pre-tensioned short-mould flow method has the following issues for special attention in the production process:

(a) If the prestress is transferred by the friction force between steel wires and concrete, it is necessary to control the deviation of steel wires in order to avoid the unevenness of prestress between different steel wires due to the deviation in steel wire length;
(b) If the anchoring plates are used to transfer the prestress, their applicability to different types of sleepers should be considered in the process of production line and production equipment design.

Table 3. Technical characteristics of pre-tensioned short-mould flow method.

1	Energy consumption	In the process of production, the mould flows in different stations, so it needs certain power equipment and hoisting equipment, and the production energy consumption is relatively high.
2	Labour	Because the mould of single sleeper length is adopted, it is convenient to use automation equipment; therefore, the automation degree of this process production line is usually higher, and fewer workers are needed.
3	Production efficiency	The flow rate of short-mould on the production line is slightly higher than that of the long-mould method but, due to fewer sleepers in a single mould, the relative production efficiency is not high. The daily production of the short-mould flow method is around 800 to 1000 sleepers.
4	Product quality	The short mould length needs to have a large stiffness and good integrity, so the shape and dimension of sleepers can better be controlled.

6. Post-Tensioned Short-Mould Flow Method

The main difference between the production processes of the post-tensioned short-mould flow method and the pre-tensioned short-mould flow method is the time of prestress application. When the concrete gains sufficient strength, the steel wires are tensioned and the prestress can be applied to the sleeper by anchoring plates.

6.1. Process and Technical Characteristics

At present, some concrete sleeper manufacturers in Italy adopt the method of post-tensioned short-mould flow to produce prestressed concrete sleepers. The mould of 4 × 1 or 5 × 1 is commonly used in production. The typical process is shown in Figure 15.

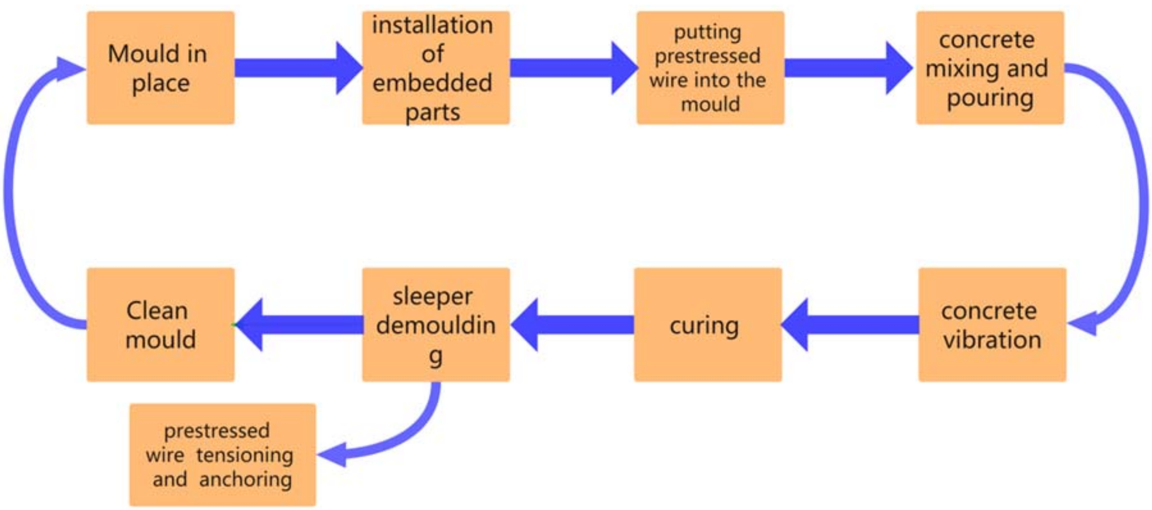

Figure 15. Main process of post-tensioned short-mould flow method.

The typical production process is shown in Figures 16–18.

Figure 16. Overview of the production line of post-tensioned short-mould flow method.

Figure 17. Post-tensioned short-mould flow method tensioning process.

Figure 18. Sealing anchor for post-tensioned short-mould flow method.

The technology of the post-tensioned short-mould flow method is relatively similar to that of the pre-tensioned short-mould flow method. The main features are shown in Table 4.

Table 4. Technical characteristics of pre-tensioned short-mould flow method.

1	Energy consumption	In the process of production, the mould flows in different stations; therefore, it needs certain power equipment and hoisting equipment, and the production energy consumption is relatively high.
2	Labour	Because the mould of single sleeper length is adopted, it is convenient to use automation equipment; therefore, the automation degree of this process production line is usually higher, fewer workers are needed.
3	Production efficiency	The flow rate of sleeper mould on the production line is slightly higher than that of the long-mould flow method, but due to the small number of sleepers in a single mould, the general production efficiency is not high. The daily production of short die flow machine group is 800 to 1000 sleepers
4	Product quality	The short mould length has a large stiffness and good integrity, so the shape and dimension of sleepers are better controlled. And the post-tensioning method is used to apply any prestress, the main reinforcement of sleepers usually uses prestressed steel with thread.

6.2. Precautions in Production

The production of prestressed concrete sleepers by the post-tensioned short-mould flow method has the following concerns for special attention in the production process:

(a) Because the post-tensioned short-mould flow method is unbonded or weakly bonded between the prestressed steel tendons and concrete in the sleeper, it is necessary to control the state of the anchor plates and the concrete ends to prevent the influence of the prestressing effect of the sleepers;
(b) Need to strictly control the quality and tension of prestressed steel tendons to avoid the fracture of steel wires due to over-tension or material.

7. Instant-Demoulded Short-Mould Flow Method

This production process of concrete sleepers is a technology that removes the sleepers immediately after the concrete gains hardening in the mould and then carries on the sleeper curing without mould. In this production process, the sleeper generally adopts the post-tensioning method to transfer the prestress through the end of the anchor plates, and the length of the mould is generally the length of a single sleeper. The quality control of sleeper appearance after demoulding is difficult. On this ground, the application range of this sleeper production technology is uncommon.

7.1. Process and Technical Characteristics

The production process of this instant-demoulded short-mould flow method is similar to the post-tensioned short-mould flow method; the main difference is the time of sleeper demoulding. The common process is shown in Figure 19.

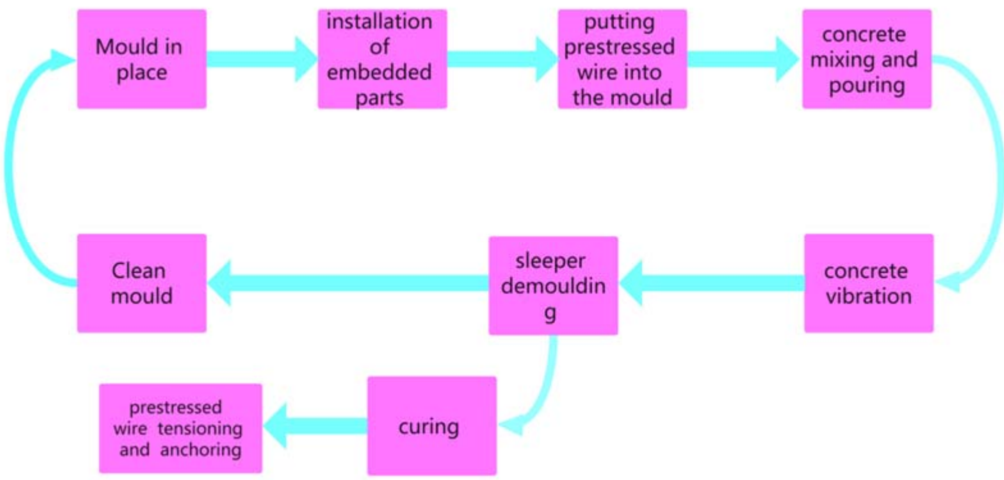

Figure 19. Main process of instant-demoulded short-mould flow method.

For the instant-demoulded short-mould flow method, the typical production process is shown in Figures 20–22.

Figure 20. Overview of the production line of instant-demoulded short-mould flow method.

Figure 21. Instant-demoulded short-mould flow method demoulding process.

Figure 22. Tensioning and anchoring process of the instant-demoulded short-mould flow method.

The main features of the instant-demoulded short-mould flow method are shown in Table 5.

Table 5. Technical characteristics of instant-demoulded short-mould flow method.

1	Energy consumption	In the process of production, the mould flows in different stations; therefore, it needs certain power equipment and hoisting equipment, and the production energy consumption is relatively high.
2	Labour	Because the mould of single sleeper length is adopted, it is convenient to use automation equipment; therefore, the automation degree of this process production line is usually higher, and fewer workers are needed.
3	Production efficiency	The flow rate of sleeper mould on the production line is slightly higher than that of the long-mould flow method, but due to the small number of sleepers in a single mould, the general production efficiency is not high. The daily production of short die flow machine group is 800 to 1000 sleepers
4	Product quality	Since the sleeper is required to maintain the shape after demoulding, the slump of concrete for sleeper production is important. Moreover, because the post-tensioning method is used to apply prestress, the main reinforcement of sleepers usually uses prestressed steel tendons with thread and anchor plates. Finally, because sleepers are not cured in the moulds, the sleeper curing temperature and humidity are easier to maintain.

7.2. Precautions in Production

The production of prestressed concrete sleepers by the instant-demoulded short-mould flow method has the following issues for consideration in the production process:

(a) Because the sleeper is demoulded immediately after the concrete hardening is completed, it is necessary to strictly control the slump of concrete to maintain acceptable shapes of the sleeper;
(b) Because the instant-demoulded short-mould flow method makes use of the post-tensioning method to apply a prestress, there is no bond or weak bond between prestressed steel tendons and concrete in sleepers; therefore, it is necessary to control the quality of anchor plates and concrete ends to prevent the influence of prestress bursting;
(c) The quality and tension of prestressed steel tendons should be strictly controlled to avoid fracture due to over-tension or any material defect.

8. Comparative Analysis of Economic Impacts of Railway Sleeper Production Methods

Prestressed concrete sleepers are employed over a long term in any ballasted railway track. To compare among different production methods of concrete sleepers, in addition to technical characteristics analysis, an economic analysis is also essential.

There are many factors affecting the economy of sleeper production methods, including raw material cost, equipment cost, labour cost, technical level, production scale and logistics condition, etc. Based on the current common production equipment and technical level of the sleepers, the technology and economy of the different production methods of the individual production line are assessed as shown in Table 6.

Table 6. Comparative analysis on economy of railway sleeper production methods.

Production Methods	Labour	Daily Capacity	Equipment Cost
Long Line System Method	About 20 persons	About 700	Low
Pre-tensioned Long-mould Flow Method	About 50 persons	About 1200	Low
Pre-tensioned Short-mould Flow Method	About 25 persons	About 800	Medium
Post-tensioned Short-mould Flow Method	About 25 persons	About 800	Medium
Instant-demoulded Short-mould Flow Method	About 20 persons	About 700	High

The comparison in Table 7 shows that:

(a) The production process of the long-line system method is simple, equipment input and equipment energy consumption are low, fewer workers are needed and each production line needs only about 20 people; therefore, the investment cost of the production line is low. On the other side, the production efficiency of this method is low; the daily production capacity of each line is usually about 700 sleepers.

(b) For the pre-tensioned long-mould flow method, the production efficiency is high; usually, the daily production capacity of each line is about 1200 sleepers. Furthermore, for the pre-tensioned long-mould flow method, the production process is simple, and the input cost of equipment is low; however, the automation degree is low, a lot of labour (generally need 50 workers each line) is required and the energy consumption of equipment is large. Therefore, the production environment of the workshop is poor.

(c) The pre-tensioned short-mould flow method and post-tensioned short-mould flow method are similar to the production efficiency and economy. The main difference is in the mode of prestressed wire tension, the daily production capacity of these two production processes is similar, the daily production capacity of each line is usually about 800 sleepers, and the input of production equipment is at the medium level.

(d) The instant-demoulded short-mould flow method has high equipment investment in the production line and low production efficiency. Usually, the daily production capacity of each line is about 700 sleepers. The main characteristic of the production process is a high degree of automation, and each production line needs only about 20 people, considering that the process has strict process control requirements in the production process; hence this method is less used.

Table 7. The carbon emission coefficient [24,25].

Coefficient	I1 Value
Carbon emission coefficient of reinforcement	CO_2 emission of 1-ton reinforcement is 3.1 kg
Cement carbon emission coefficient	CO_2 emission of 1-ton cement is 3.1 kg
The carbon emission coefficient of the coarse aggregate	Power consumption of 1 ton of coarse aggregate is 1.17 kW, oil consumption is 0.723 L, convert into CO_2 emission is 3.12 kg
Carbon emission coefficient of fine aggregate	consumption of 1 ton of fine aggregate is 1.5 kW, oil consumption is 0.78 L, convert into CO_2 emission is 3.66 kg
Energy-carbon emission coefficient	Consumption of 1 kW energy, convert into CO_2 emission is 1.00 kg

In the design and construction of the actual sleeper production line, a detailed budget analysis for different production processes according to the actual working conditions should be taken into account.

9. Comparative Analysis Carbon Emissions of the Railway Sleeper for Different Production Methods

9.1. Time Boundary and Carbon Emission Activity

According to the life cycle evaluation theory, it is divided into four steps: calculation object and range determination, list analysis, determination of calculation model calculation and impact evaluation [24–26]. The production of prestressed concrete sleepers at the time boundary includes production and transportation of raw materials, production of prestressed concrete sleepers, construction and use of prestressed concrete sleepers and removal and recovery of prestressed concrete sleepers. Considering the small carbon emission of prestressed concrete sleepers in the later construction, use and demolition stage, the study time boundary is determined as concrete raw material production as the starting point and taking prestressed concrete sleeper production and moulding as the endpoint. The carbon emission of prestressed concrete sleepers under different production process conditions within this time range is calculated.

To analyse the carbon emission activities of prestressed concrete sleepers, we. first determine the system boundary, namely the carbon emission source and emission composition, as shown in Figure 23. Prestressed concrete sleeper production can be decomposed into the production and transportation process of raw materials, concrete preparation process and prestressed concrete sleeper production process. The carbon emission activities of each process are analysed as follows.

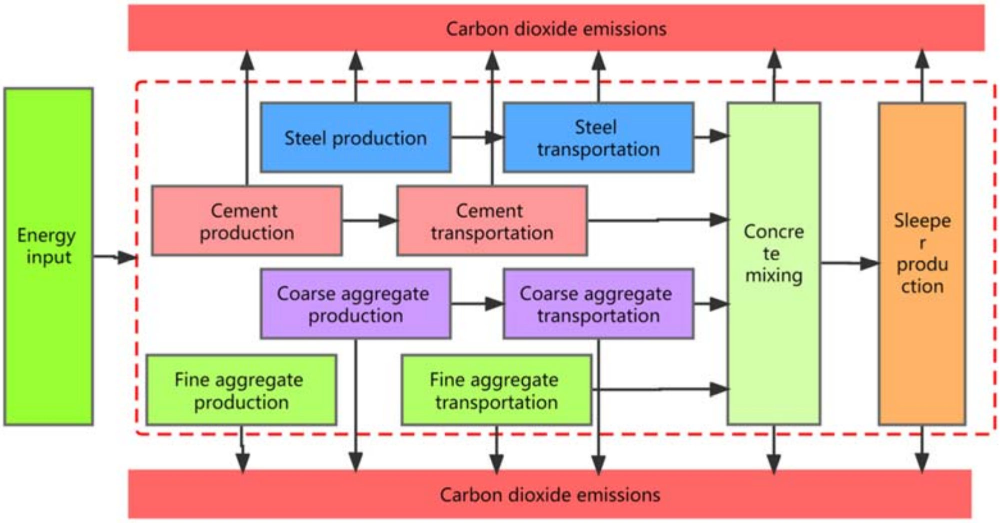

Figure 23. Analysis of carbon emissions of prestressed concrete sleeper production.

Specific activities of carbon emissions during the production of prestressed concrete sleepers include:

(a) Carbon emissions from steel in the factory and fuel consumption of steel to the sleeper plant.
(b) Carbon emissions from cement production in the factory and from fuel consumption from cement transportation to the sleeper production plant.
(c) Carbon emissions of coarse aggregate at the plant and fuel consumption of coarse aggregate to the sleeper plant.
(d) Carbon emissions from fine aggregate at the plant and fuel consumption of fine aggregate to the sleeper plant.
(e) Energy consumption during concrete mixing production and the carbon emissions from fuel.
(f) Energy consumption and fuel carbon emissions during the prestressed concrete sleeper production phase.

9.2. Calculation Model

Based on the analysis of carbon emission activities of the production, the calculation model of carbon emission of prestressed concrete sleeper is established as follows:

$$C_T = C_1 + C_2 + C_3 + C_4 + C_5 + C_6 \tag{1}$$

In the formula:

C_T is the total carbon emission of the whole production of prestressed concrete sleepers;

C_1 is the carbon emission of steel bar production process and transportation process;

C_2 is the carbon emission of the cement production process and transportation process;

C_3 is the carbon emission of the production and transportation process of coarse aggregate;

C_4 is the carbon emission of the production and transportation process of fine aggregate;

C_5 is the carbon emission of the concrete mixing process;

C_6 is the carbon emission during prestressed concrete sleeper production.

Carbon emission Q_1 during the production processing of reinforcement, cement, coarse aggregate and fine aggregate is calculated in the following formula:

$$Q_1 = NI_1 \tag{2}$$

In formula:
N is the material quantity;
I_1 is the CO_2 emission in the unit quantity of material (see Table 7).
The carbon emission Q_2 caused by oil consumption during concrete mixing and prestressed concrete sleeper production is calculated in the following formula:

$$Q_2 = PMI_2 \tag{3}$$

In the formula:
P is the oil consumption per unit output;
M is the output;
I_2 is the emission coefficient of CO_2 emissions per unit of oil consumption.
The carbon emission Q_3 caused by power consumption during concrete mixing and prestressed concrete sleeper production is calculated in the following formula:

$$Q_3 = DMI_3 \tag{4}$$

In the formula:
D is the power consumption per unit output;
M is the output;
I_3 is the emission coefficient of CO_2 emissions per unit of power consumption.
The carbon emission Y caused by the material transportation process is calculated in the following formula:

$$Y = EFLN \tag{5}$$

In the formula:
E is the unit of energy consumption of transportation (gasoline truck transportation 3.038 MJ $(t\ km)^{-1}$ and diesel vehicle transportation 2.055 MJ $(t\ km)^{-1}$;
F is the carbon emission coefficient of the corresponding fuel during transportation (see Table 8);
L is the transportation distance;
N is the amount of material.

Table 8. Effective carbon emission coefficient F of some fuel [24,25].

Fuel Type	Carbon Deficiency ($kg\cdot CJ^{-1}$)	Default of Carbon Oxide Factor	Effective CO_2 Emission Factor ($kg\cdot TJ^{-1}$)		
	A	B	Default Value C = AB $\times$ 44/1.2 $\times$ 10^4	95% Confidence Interval	
				Low	High
Automobile gasoline	18.9	1	69,300	67,500	73,000
Aiesel oil	20.2	1	74,100	72,600	74,800

9.3. Calculation of Carbon Emissions of the Railway Sleeper Production

The carbon emissions are calculated and analysed by a typical prestressed concrete sleeper structure (as shown in Figure 24). This type is Grade C60 concrete with 0.14 m^3, reinforcement of 7.9 kg. The main raw materials of concrete are cement, water, coarse aggregate and fine aggregate, excluding admixtures. Specific processes for different production methods are shown above.

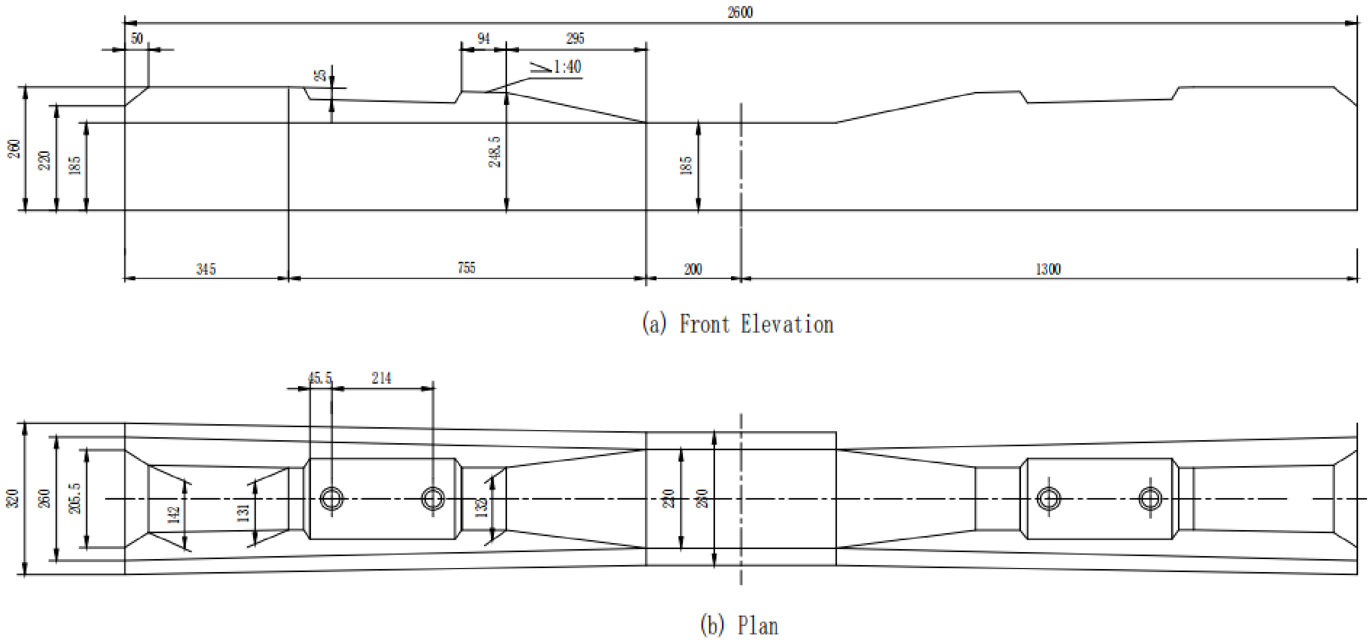

Figure 24. Prestressed concrete sleeper geometric details.

The material dosage of prestressed concrete sleeper 1 m^3 concrete is cement 450 kg, water 126.5 kg; coarse aggregate 1224 kg; and fine aggregate 650 kg. During the transportation of raw materials, the transportation distance is 100 km, and the actual consumption of various materials in concrete mixing and sleeper production is 1%.

Based on the above principles and relevant parameters of prestressed concrete sleepers, the carbon emissions in the prestressed concrete sleeper production of different production methods are calculated as shown in Table 9, and the carbon emissions of different stages as the percentage of the sleeper production are shown in Table 10.

Table 9. Carbon emissions from production of single prestressed concrete sleeper (kg).

Production Methods	Carbon Emission of Steel Bar C_1	Carbon Emission of the Cement C_2	Carbon Emission of Coarse Aggregate C_3	Carbon Emission of Fine Aggregate C_4	Carbon Emission of the Concrete Mixing C_5	Carbon Emission of Sleeper Production C_6	Total Carbon Emission C_T
Long-line system method	0.19	52.24	4.18	2.27	0.58	1.03	60.50
Pre-tensioned long-mould flow method	0.19	52.24	4.18	2.27	0.34	1.39	60.62
Pre-tensioned short-mould flow method	0.19	52.24	4.18	2.27	0.51	2.50	61.90
Post-tensioned short-mould flow method	0.19	52.24	4.18	2.27	0.51	2.20	61.60
Instant-demoulded short-mould flow Method	0.19	52.24	4.18	2.27	0.58	2.86	62.33

Table 10. The proportion of carbon emissions at different stages.

Production Methods	Carbon Emission of Steel Bar C_1	Carbon Emission of the Cement C_2	Carbon Emission of Coarse Aggregate C_3	Carbon Emission of Fine Aggregate C_4	Carbon Emission of the Concrete Mixing C_5	Carbon Emission of Sleeper Production C_6
Long-line system method	0.32%	86.35%	6.91%	3.75%	0.96%	1.70%
Pre-tensioned long-mould flow method	0.32%	86.18%	6.90%	3.75%	0.56%	2.30%
Pre-tensioned short-mould flow method	0.31%	84.40%	6.76%	3.67%	0.82%	4.04%
Post-tensioned short-mould flow method	0.31%	84.81%	6.79%	3.69%	0.83%	3.57%
Instant-demoulded short-mould flow Method	0.31%	83.82%	6.71%	3.64%	0.94%	4.58%

The calculation results in Table 10 show that:

(a) The five production methods have the same carbon emissions of raw materials, but the carbon emissions of concrete mixing and sleeper production are different, mainly due to different energy consumption. The long line system method has the minimum carbon emission of the single sleeper, for which the value is 60.50 kg, and the instant-demoulded short-mould flow method has the maximum life cycle carbon emission of the single sleeper, for which the value is 62.33 kg.

(b) The calculation results of the sleeper carbon emissions show that the carbon emission of cement is the largest, and the carbon emissions of cement corresponding to the five production methods account for about 85% of the total emission. Therefore, for the coordination ratio of prestressed concrete sleepers, reducing the use of cement is an effective measure to reduce the carbon emission of concrete sleepers.

10. Conclusions

Railway prestressed concrete sleepers are an important component of ballasted track structures. In this paper, the state-of-the-art analyses of technical characteristics and precautions of prestressed concrete sleeper production are highlighted:

(a) Through the comparative analysis of the economy and the quality level of the production methods, we can see that the efficiency of the long-line system method is not high, but the cost of labour, equipment and energy consumption needed is also less. The production method of the pre-tensioned long-mould flow method has high efficiency and low cost of equipment but more workers are needed and the daily energy consumption in production is large. The automation level of the pre-tensioned short-mould flow method and post-tensioned short-mould flow method is higher, so the equipment cost is higher and less labour is required. Although the automatic degree of the instant-demoulded short-mould flow method is high, the control of the process is strict and the quality level of the sleeper is normal; therefore, it is not the mainstream choice of the sleeper production.

(b) For the long-line system method, the change of temperature will cause the deformation of steel wires and lead to the difference between the prestress and the design prestress. Therefore, an appropriate temperature should be controlled during the prestressed force transmitting to ensure the prestressed force of steel wires meets the design requirements. For the long-mould flow method, the mould must have sufficient stiffness, and the influence of tension force and self-weight on the deformation of the mould should be considered in order to avoid the wire deflection and prestress loss. For the pre-tensioned short-mould flow method, if the prestress is transferred by the friction force between steel wires and concrete, it is necessary to control the deviation of steel wires in order to avoid the unevenness of prestress between different steel wires due to the deviation of steel wire length. For the post-tensioned short-mould flow method, it is necessary to control the state of the anchor plates and the concrete ends to prevent the influence of the prestressing effect of the sleepers. For the instant-demoulded short-mould flow method, it is necessary to strictly control the slump of concrete to maintain acceptable shapes of the sleeper.

(c) The different production methods have the same carbon emissions of raw materials, but the carbon emissions of concrete mixing and sleeper production are different, mainly due to different energy consumption. The long line system method has the minimum carbon emission of the single sleeper, for which the value is 60.50 kg, and the instant-demoulded short-mould flow method has the maximum life cycle carbon emission of the single sleeper, for which the value is 62.33 kg.

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