Analysis of structure and mixing characteristics of a double barrel with differential velocity based on theory and discrete element simulation

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Abstract. The double barrel (DB) is the essential functional part of continuous asphalt mixing equipment, which affects the mixing uniformity of asphalt mixture. To improve the mixing uniformity of the mixture, a double barrel with differential velocity (DBDV) was proposed. The structure of DBDV and its influence on the mixing uniformity of the mixture were described. The current double barrel is divided into single horizontal shaft DB and double horizontal shaft DBDV. The discrete element simulation is used to compare the mixing uniformity of two kinds of DB. The results show that the mixing uniformity of double horizontal shaft DBDV is better than that of the single horizontal shaft DB, proving the correctness and rationality of the above analysis.

1. Introduction

Continuous asphalt mixture mixing equipment is a kind of equipment that can continuously produce mixture, which is composed of cold material supply system, drying system, mixing system, storage system, etc. [1-2]. In the traditional continuous asphalt mixing equipment, the drying system (i.e., drying drum) and mixing system (i.e., continuous mixer) are operated separately. To save energy and protect the environment, American scholar BROCK, J. DONALD invented a continuous drying mixer (i.e., double barrel) which combines drying system and mixing system [3], as shown in Figure 1 [4].

Figure 1. DB model.

The double barrel can not only realize the drying of aggregate and mixing of mixture but also work on RAP material. The advantages of this structure equipment are 1) RAP material has no direct
contact with open fire, which prevents the aging of asphalt in the heating process of RAP material; 2) the asphalt smoke generated in the mixing area is sucked into the inner drum and discharged after being burned by the flame, which prevents environmental pollution; 3) the heating of RAP material mainly depends on the hot smoke generated in the drying area and the hot of virgin aggregate and rotary drum, energy has been secondary utilization to avoid the waste of energy.

Although it has many advantages, the quality of its mixture has been questioned, which leads to its not widely used. To solve this problem, scholars have put forward some solutions [4-10], such as changing the structure of the mixing blade to increase the range of the material being scattered, adding pre mixing device, and adding the second mixing drum or mixer to improve the quality of the mixture. However, in the above scheme, either the uniformity of fine particles is not solved, or the floor area and energy consumption increase. Based on this, a scheme (i.e., double barrel with differential velocity (DBDV)) is proposed to solve the mixture quality problem in this study. The structure design of DBDV is described, and the influence of DBDV on mixing uniformity is analyzed theoretically. The feasibility of the proposed scheme is verified by simulation.

2. Structure design of DBDV

Because the inner drum part of DBDV is the same as DB, the model of DBDV is simplified. For example, the condition flights, showing flights and combustion flights in the inner drum are not drawn, and the length of the inner drum is shortened, as shown in Figure 2. Compared with Figure 1, the difference is that a mixing shaft is added in the mixing chamber.

![Figure 2. DBDV model.](image)

The key to the design of DBDV lies in the arrangement of the flights on the mixing shaft and the determination of the installation position. The cross-section of the differential velocity region is shown in Figure 3.

![Figure 3. Cross-section of differential velocity zone.](image)
From Figure 3,

\[
\begin{align*}
R_1 &= 2R_0 + r_i - R_0 - W \\
R_2 - R_0 &= r_2 - r_i \\
R_3 &= r_2 + R_0 \sin \alpha \\
r_i &= R_0 - [(2\eta - I)R_0 - \mu l] \sin \alpha / (I + \sin \alpha)
\end{align*}
\]

(1)

Where \( \beta, \eta \) and \( \mu \) are the scale factors between \( R_2 \) and \( R_0 \), between \( R_1 \) and \( R_0 \), and between \( W \) and \( l \), respectively. \( R_i \) \((i=0,1,2)\) is the radius of the inner drum, rotating blade, and shell, respectively. \( R_3 \) is the installation radius of the mixing shaft. \( r_i \) are the radius of the mixing shaft and the shell where the mixing shaft is located, respectively. \( \alpha \) is the angle between the line of the inner drum and the mixing shaft and the horizontal line. \( W \) is the width of the mixing flight. \( l \) is the length of the mixing flight.

\( l \) in Equation (2) is determined by the axial overlap coefficient of the flight. The axial overlap coefficient of the mixing flights can be defined as the ratio of the total axial length of the distance between the mixing flights to the total axial length of the mixing flights, namely

\[
\xi = \frac{\sum_{i=1}^{n} N_i l_i \cdot \cos \phi_i}{l} = \frac{L}{\sum_{i=1}^{n} N_i l_i \cdot \cos \phi_i} - 1
\]

(3)

Where \( \xi \) is the axial overlap coefficient. \( L \) is the length of the differential velocity zone, which is half of the total length of the mixing zone. \( N_i \) is the axial number of the \( i \)th mixing flights. \( \phi_i \) is the installation angle of the \( i \)th mixing flight.

To prevent interference between the flights, the initial installation positions of the mixing shaft and the inner drum are shown in Figure 4. And the relationship between runs should meet Equation (4).

\[
i = \frac{n_2}{n_1} = \frac{z_1}{z_2}
\]

(4)

Where \( i \) is the differential velocity ratio. \( n_1 \) and \( n_2 \) are the rotary speeds of the inner drum and mixing shaft, respectively. \( z_1 \) and \( z_2 \) are the rows of rotating blades on the inner drum and mixing shaft, respectively.

3. **Influence of DBDV on mixing uniformity of asphalt mixture**

The mixing uniformity of the mixture directly affects the quality of the pavement [11]. To control the mixing uniformity of the mixture, it is necessary to find out the influence factors of DBDV on the mixing uniformity and their relationship.
Compared with DB, there are three motion modes of the mixture in the DBDV: axial motion, circumferential motion, and transverse convection motion. It is beneficial to the mixing uniformity of the mixture in DBDV. The axial movement makes the material move to the outlet, the circumferential movement makes the material move along the circumferential direction, and the transverse convection movement makes the material realize the transverse exchange movement. The mixing coefficient can characterize them.

The axial mixing coefficient represents the ratio of the axial length of the mixture to the axial length of the flight [12]. The circumferential mixing coefficient represents the ratio of the piled area of the mixture on the mixing flight to its area of the maximum [12]. Figure 5 shows the material on the flight at a specific time. Equation (5) can be obtained from Figure 5.

\[
\begin{align*}
    k_a & = \frac{a - b}{a + b} = \frac{\tan(\varphi - \lambda)}{\tan \theta} \\
    S & = \frac{l^2}{4} [\tan \theta \cos^2 (\varphi - \lambda) - \cot \theta \sin^2 (\varphi - \lambda)] \\
    k_c & = \frac{S}{S_{\text{max}}} = \cos^2 (\varphi - \lambda) - \cot^2 \theta \sin^2 (\varphi - \lambda)
\end{align*}
\]  

(5)

Where \(k_a\) and \(k_c\) represent the axial mixing coefficient and circumferential mixing coefficient, respectively. \(\theta\) is the stacking angle of the mixture. \(\lambda\) is the inclination of the drum. \(S\) is the piled area of the mixture. \(a\) and \(b\) denote the axial length of the side of the stacked mixture.

\[\text{Figure 5. Material piled on mixing blades.}\]

\[\text{Figure 6. Cross-section of DBDV.}\]
Figure 6 shows a schematic of a cross-section of the DBDV. Let I or III denote the non-convective region, and II denote the flight overlap region, i.e., the convective region.

The transverse convection mixing coefficient can be expressed as [13]

\[ k = \frac{N' \cdot \Delta m}{m} \] (6)

Where \( k \) is the transverse convective mixing coefficient, \( N' \) is the circumferential number of mixing flights, \( \Delta m \) is the mass of material exchanged by a single blade, and \( m \) is the mass of the mixture in III or I.

Here, regions III and II are the research objects. When the inner drum is rotated for one revolution, the exchange capacity of materials from III to II is \( N_1 \Delta m_i \), and that from II to III is \( iN_2 \Delta m_i \). After the exchange, the surplus of a specific component material in III is

\[ m \cdot i_{3,1} = m \cdot i_3 - N_1 \cdot \Delta m \cdot i_3 + i \cdot N_2 \cdot \Delta m \cdot i_2 \] (7)

Then, when the inner drum rotates \( n \) turns,

\[ i_{3,n} = i_3 + k(i \cdot i_2 - i_3)(1 + (1 - k) + \cdots + (1 - k)^{n-1}) \] (8)

Where \( i_3 \) is the relative proportion of a specific component in the mixture in zone I, \( N_1 \) and \( N_2 \) are the circumferential numbers of mixing blades on the inner drum and mixing shaft, respectively.

It is assumed that the relative content of components in zone II is 1, i.e.,

\[ i_2 = \frac{2i_2}{i_1 + i_3} = 1 \] (9)

Where \( i_1 \), \( i_2 \), and \( i_3 \) represent the absolute content of a specific component in I, II, and III, respectively.

Substituting Equation (9) into Equation (8), Equation (10) can be obtained, namely

\[ \log(1 - k) = \frac{\log(i - i_{3,n}) - \log(i - i_3)}{n} \] (10)

Through the above analysis, it can be concluded that the factors affecting the mixing uniformity of the mixture in DBDV are the structure parameters (installation angle of mixing flight \( \phi \), drum inclination \( \lambda \)), motion parameters (rotation speed of rotary drum \( n \), differential velocity ratio \( i \)), and use parameters (proportion of specific component in mixture \( i_3 \)).

4. Simulation verification of mixing uniformity

Through the previous analysis, the current double barrel can be divided into two categories, namely single horizontal shaft DB and double horizontal shaft DBDV. To compare the mixing uniformity with the existing scheme, the discrete element method was used. The simulation results of two kinds of the double barrel under the optimal parameter matching were compared. The parameters considered in this study are blade installation angle, drum inclination, and linear speed of the rotating drum. And the simulation model is a quarter of the original model. Table 1 [14-15] shows the input parameters used in the EDEM simulation. Equation (11) [16-17] shows the parameters characterizing the mixing uniformity. Table 2 shows the results of the comparison. It can be seen from the comparison results that the mixing uniformity of double horizontal shaft DBDV is better than that of single horizontal shaft DB, especially for fine particles.
Table 1. Summary of EDEM input parameters.

| Materials | Properties                  | Value          |
|-----------|-----------------------------|----------------|
| Particle  | Diameter (mm)               | 19, 9.5, 4.75  |
|           | Productivity (kg/s)         | 0.316, 1.26, 0.254 |
|           | Density (kg/m$^3$)          | 2900           |
|           | Poisson’s ratio             | 0.25           |
|           | Shear modulus (Pa)          | 1.38e7         |
| Geometry  | Density (kg/m$^3$)          | 7800           |
|           | Poisson’s ratio             | 0.3            |
|           | Shear modulus (Pa)          | 7.5e7          |
|           | Differential velocity ratio | 2              |
| Particle–particle | Coefficient of restitution | 0.45          |
|           | Coefficient of static friction | 0.55       |
|           | Coefficient of rolling friction | 0.3      |
| Particle-geometry | Coefficient of restitution | 0.5          |
|           | Coefficient of static friction | 0.45      |
|           | Coefficient of rolling friction | 0.3      |
| Time step (s) |                               | 4.5e-5 s      |
| Contact model  |                                   | Hertz–Mindlin |
| Cell size     |                                   | 3.5 R (R=2.375) |

\[
\begin{align*}
\delta &= e^{-\xi} \\
\xi &= \frac{1}{\overline{\varepsilon}} \left[\sum_{i=1}^{n} (\varepsilon_i - \overline{\varepsilon})^2\right]^{1/2} \\
\end{align*}
\]

Where $\delta$ is the dispersion coefficient, $\xi$ is the coefficient of variation, $\varepsilon_i$ is the proportion of particles in the $i$th grid, and $\overline{\varepsilon}$ is the average of $\varepsilon_i$.

Table 2. Comparison of uniformity.

| Model | $\phi$ (°) | Linear velocity (m/s) | $\lambda$ (°) | $\delta$ | $\phi$ (°) | Linear velocity (m/s) | $\lambda$ (°) | $\delta$ |
|-------|------------|-----------------------|--------------|---------|------------|-----------------------|--------------|---------|
|       |            | 19                    | 9.5          | 4.75    | 19         | 9.5                   | 4.75         |         |
| DBDV  | 45         | 0.90                  | 3.155        | 0.872   | 0.957      | 0.782                 |              |         |
| DB    |            | 1.29                  | 4.218        | 0.765   | 0.652      | 0.783                 |              |         |
| Relative error |        | 13.99%                | 4.93%        | 34.13%  |            |                       |              |         |

5. Conclusions
The DBDV was proposed, and its structure, working characteristics, and influence on mixing uniformity were analyzed. The mixing uniformity of the proposed scheme and the existing scheme was compared by the simulation method. The conclusions are as follows.

1) The DB of continuous asphalt mixing equipment can be divided into single horizontal shaft DB and double horizontal shaft DBDV.

2) Compared with single horizontal shaft DB, the mixing of the mixture in double horizontal shaft DBDV has transverse convection motion, which can effectively alleviate the problem of poor mixing uniformity caused by the inability of fine particles to be stirred.

3) The factors affecting the mixing uniformity of the mixture in double horizontal shaft DBDV are the structure parameters, motion parameters, and using parameters.
4) The mixing uniformity of the double horizontal shaft DBDV is better than that of the single horizontal shaft DB. The dispersion coefficient of coarse particles, moderate particles, and fine particles are increased by 13.99%, 4.93%, and 34.13%, respectively.

Acknowledgements
This work is supported by the support of the key science and technology projects in transportation industry (2020-MSI-051) and science and technology program of Tibet autonomous region (XZ2019TL-G-02).

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