Abrasive wear and optimal installation angle of concrete double-horizontal shaft mixer stirring blades

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Received: 7 February 2020 / Accepted: 15 April 2020 / Published online: 12 May 2020
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Abstract

The quality of a building desponds directly on the quality of concrete, and mixing is the key process of concrete production. However, a mixing blade is severely worn and has a relatively short life during the mixing process because of severe friction between the concrete material and the double-horizontal shaft mixer stirring blades. This study uses the abrasion mechanism of a mixer and the abrasive wear formula as bases to analyze the theoretical maximum line wear rate η of an experimental prototype at five blade installation angles, and obtain the optimal installation interval and optimal installation angle. Results indicate that the wear rate of different blade installation angles changes significantly. The wear rate at 45° is the largest, and the corresponding theoretical life is only 125 days. By contrast, the wear rate at 35° is the smallest, and the corresponding theoretical life is 192 days. The change rule of the maximum line wear rate η of the blade is obtained through the wear line chart, and the performance curve and evaluation function are fitted using MATLAB. The three aspects of stirring quality, energy consumption, and wear loss are quantitatively analyzed. The best installation angle and interval are 31.8° and 30°–34°. This study can provide a reference for the design choice of the installation angle of the mixing blade of concrete mixers.

Keywords Double-shaft concrete mixing · Mixing blade · Maximum line wear rate η · Optimal installation angle

1 Introduction

The rapid development of China's urbanization has resulted in the significant increase in the number of buildings in cities, thereby placing considerably high requirements on the quality of buildings. The quality of concrete directly determines whether the building quality is qualified and has a direct relationship with the mixing effect of mixers. During the mixing process, blade wear is intensified owing to the severe friction caused by the concrete material to the mixing blade, and the mixing effect is significantly reduced with time. Therefore, blade wear should be studied and the optimal blade installation angle of mixers should be determined to reduce loss and improve the mixing quality.

Many institutions have been studying the design and production of twin-shaft forced concrete mixers, such as BHS-Sansohofen Machinery and Mining Company (Germany), Shimao Company (Italy), Jensen Company (US), and Nikkei Co., Ltd. (Japan). Feign researchers have found that the different arrangements of mixing blades in concrete mixing could cause significant differences in the mixing effects. Complex abrasion of stirring blades occurred during the stirring process. Valigi et al. demonstrated and discussed the geometry of an improved planetary concrete mixer blade from the perspective of abrasion resistance, estimated the differences through 2D evaluation, and evaluated the wear resistance of several new types of blades and extended wear life with reduced wear rate by optimizing new design [1]. Moreover, Valigi et al. used 3D optical

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scanners in proposing a new validation procedure of mixing blades in terms of wear resistance and efficiency, and assessed the efficiency and material loss of mixers by using 3D metrological instrument [2], which provides a basis for the selection of blade materials in this paper. Jurevičius et al. analyzed the causes of wear of rotating blade mixers, the most important of which was the adhesion of particles between the blade end and the bottom [3]. This provides a reference for the wear of the stone on the stirring blade in this article. Niranatlumpong et al. proposed a surface wear-resistant treatment for the blades of crushers to provide a reference for the treatment of mixer blades [4]. Tang et al. used a certain type of double-horizontal shaft forced concrete mixer as research object and introduced the calculation formula of the line wear rate of mixing blades on the basis of abrasive wear mechanism. The calculation of the surface line wear rate of mixing blades was obtained through the calculation of the Fluent software and related post-processing [5]. The research provides a basis for the calculation of the line wear rate formula in this paper. At present, the commonly used installation angle of blade is 45° .

Various concrete material mixing methods have different effects on the mixing effect. Ferraris provided an overview of various commercially available mixers and mixing methods for concrete materials. In addition, the advantages and disadvantages of different mixers and mixing methods and their applications were also studied [6]. Rejeb studied the effects of a two-step mixing method on the properties of concrete mixtures containing superplasticizers [7], which provides a theoretical basis for studying the abrasion of the blades caused by the concrete mixing method. Chang and Peng used six mixing methods to prepare high-flow high-performance concrete (HPC). The test results identified one of the most effective and economical methods of manufacturing HPC, particularly for lower binder content, when producing materials with higher fluidity and better compressive strength than other methods, which require minimal mixing time and superplasticizers [8].

Juez et al. studied the friability of recycled concrete aggregate (RCA) during mixing to gain an improved understanding the evolution of this material during mixing and improve the design of recycled aggregate concrete mixtures [9]. Bouzoubaa studied the mechanical properties and durability of concrete made from high-volume fly ash (HVFA) blended cement with coarse fly ash that does not meet the fineness requirements of ASTM C 618. The production of HVFA mixed cement provides an effective method for using coarse fly ash [10]. The pre-mixing procedures of the two-stage mixing approach, such as Tam et al., can effectively develop some strength-enhancing chemical products, including $C_3S_2H_3$, ettringite, CH, and C_6S_3H ,

thereby indicating that RAC made by two-stage mixing approach can improve the hydration process [11]. Kasat et al. developed a comprehensive CFD model to understand solid suspension and its impact on the liquid-phase mixing process in a solid-liquid stirred reactor, and studied the predictive ability of applying CFD technology to a solid-liquid stirred vessel [12]. Mechtcherine et al. used discrete element method (DEM) to simulate concrete flow [13]. Valigi et al. studied the optimization of concrete twin-horizontal mixers in proposing a model that can evaluate the influence of design parameters on machine power consumption in the different stages of the mixing cycle [14].

Cazacliu and Roquet introduced a new concrete mixing dynamics model. This model defines five consecutive phases through which the properties of a mixture can be changed [15]. Cazacliu proposed a model for the relationship between microstructure state evolution and mixing time in concrete components [16]. Danilevskii et al. described a method to monitor the homogeneity of concrete mixture and determine its processability index on the bases of vibration level, sound, and vibration excited in the mixer during the concrete mixing process [17]. Ilesanmi et al. improved the concrete mixer. The results obtained showed that compared with the manual method, the developed concrete mixer has higher operating efficiency, shorter processing time, and higher processing capability [18]. Wallevik and wallevik analyzed the shear rate inside a concrete mixer truck and showed that the shear rate decreased exponentially with the increase in drum loading. The results also showed that for a given drum speed, the shear rate decreased with increase in plastic viscosity and yield stress [19]. Dohi found that large impellers are more effective for solid suspension than triple impeller systems [20]. In order to assess and predict the effects of abrasive wear on typical tillage machine components, Bedolla et al. developed a combined experimental and numerical simulation procedure based on a time- and space-resolved version of the Archard wear equation. The applicability of the aforementioned procedure was demonstrated on a tooth of a circular harrow. The simulated worn geometry was in good agreement with the real geometry of a tooth worn in a soil bin [21]. This provides guidance and basis for corresponding wear modeling in this article.

Machine components operating in sandy environments will wear because of the abrasive interaction with sand particles. In the book of Wen and Huang, a method was derived to predict the amount of wear caused by such abrasive action, in order to improve the maintenance concept of the components [22]. At the same time, a finite element model was used to simulate various tips scratching a smooth surface. The establishment of finite element

method for scratched surface provides a reference for the establishment of related wear models in this paper. A systematic wear model of the cylindrical grinding process with an alumina abrasive belt from the perspective of single grain sliding wear was established [23]. The results indicated that the established model was in reasonable agreement with the experimental outcomes, which suggests that this model could be useful in the industry to predict the wear process of abrasive belts [24].

The reasonableness of the blade installation angle directly affects the quality and efficiency of concrete. At present, domestic and foreign enterprises have studied the installation angle of mixers mainly from the producers' prospective. The insufficient theoretical bases of designs and imperfection of blade design have become uncertain factors restricting the performance of mixers. On the basis of the theoretical analysis of blade installation angle, the simulation and experimental research on the rationality of blade installation angle can provide theoretical support to the design of the blade installation angle of double-horizontal shaft mixer and reference for the blade installation angle design of other models.

2 Wear analysis of stirring blades

2.1 Wear mechanism

Sand and stone during the mixing process of mixers will have a more intense friction with the mixing blade compared with other concrete materials. The blade surface will wear out because of the hardness and irregular appearance of sand and stone, and the rough surface will cause corresponding wear on the blade. These two examples are the main forms of abrasive wear. The force between the sand and stone causes the abrasive to squeeze the blade surface, thereby causing the abrasive to rub against the surface of the object. Abrasive wear damages the blade surface, form grooving abrasion, and generate abrasive debris. During the stirring process, the relative sliding speed of sand on the blade surface will also cause different degrees of wear. Sand is fine-grained and the main form of friction with the blade during the stirring process is rolling friction. Moreover, the diameter of the stone is considerably larger than that of the sand, and the sliding friction mainly occurs during the stirring process. By contrast, stones produce substantially intense friction on the blades. Wear theory states that the amount of wear is proportional to the size of the abrasive particles, and the particle diameter of stones is considerably larger than that of sand. In addition, sand surface is relatively smooth under long-term water erosion. Therefore, the surface wear caused by stone is evidently serious [5, 22].

2.2 Wear calculation theory

The foregoing abrasion mechanism indicates that stone is the main abrasive particle that causes the abrasive wear of stirring blades. Accordingly, the corresponding calculation formula of line wear η is obtained as follows [5, 22]:

$$\frac{dh}{ds} = K \frac{p}{H}, \quad (1)$$

where dh is the wear thickness of the surface, ds is the relative sliding distance, K is the wear coefficient, p is the surface pressure of the stirring blade, and H is the material hardness of the stirring blade.

Formula (1) indicates that the theoretical line wear rate η^* of the blade can be derived as follows:

$$\eta^* = \frac{dh}{ds} \cdot \frac{ds}{dt} = K \cdot \frac{p}{H} \cdot v. \quad (2)$$

The volume fraction of stone in concrete is ζ , which can reflect the probability of abrasive wear caused by contacting and sliding between the blades and stones during the mixing process. Hence, the revised blade line wear rate η formula is as follows:

$$\eta = \eta^* \cdot \zeta = \frac{dh}{ds} \cdot \frac{ds}{dt} \cdot \zeta = K \cdot \frac{p}{H} \cdot v \cdot \zeta, \quad (3)$$

where η represents the revised line wear rate and v is the relative sliding speed.

Formula (2) indicates that when the wear coefficient K is constant, the wear rate is proportional to the load during wear and inversely proportional to the hardness of the blade material. However, results of normal working conditions and some simulation experiments indicate that the abrasive wear coefficient K is not constant. Accordingly, the value of K is related to the relative size between the abrasive entities hardness (H_a) and hardness (H_m) of materials to be grounded. In general, relative wear occurs in three areas: (a) low wear zone, where $1.25 H_a < H_m$ and the wear coefficient K is proportional to H_m^{-6} ; (b) excessive wear zone, where $0.8 H_a < H_m < 1.25 H_a$ and the wear coefficient K is proportional to $H_m^{-2.5}$; and (c) high wear zone, where $H_m < 0.8 H_a$ and the wear coefficient K remains constant [22].

The material of the stirring blade was set to gray cast iron with Poisson's ratio of 0.27, elastic modulus of 66 MPa, yield limit of 572 MPa, and Brinell hardness of 210 HBS. The mixing material is a homogeneous concrete fluid material. The specific material properties are as follows: dynamic viscosity is 100 kg/(m s) and density ρ is 2350 kg/m³. The aggregate is basalt, the density ρ is 3000 kg/m³, and Brinell hardness is approximately 485 HBS. The volume fraction of the aggregate in concrete is 31.6%. Thus, the volume

fraction of stones in homogeneous concrete in formula (3) is $\zeta = 31.6\%$.

The characteristics of abrasive wear indicate that the ratio of the hardness of the abrasive ($H_a = 485\text{HBS}$) and hardness of the material to be grounded ($H_m = 210\text{HBS}$) is 2.31. Thus, $0.8 H_a = 388\text{HBS} > H_m$. Evidently, abrasive wear is in a high wear zone. Its wear coefficient K remains constant (i.e., $K = 8 \times 10^{-5}$) [6].

2.3 Pressure and speed distribution of stirring blades

The stirring blade model is shown in Fig. 1. To facilitate the research, the stirring blades are labeled as shown in the figure.

The calculation results of the symmetrically distributed mechanism are the same owing to the symmetrical relationship of the stirring mechanism. Hence, only the blades on one of the stirring mechanisms are used as research object for the analysis. After processing using the post-processing software Tecplot, the surface pressure distributions of the stirring mechanism at five blade installation angles were obtained, as shown in Fig. 2.

As shown in Fig. 2, the maximum pressure distribution is at the top surface of the stirring blade, and the maximum values at the installation angles of 30° , 35° , 40° , 45° , and 50° are 14.4, 13.1, 15.1, 16.1, and 13.5 kPa, respectively. The

Fig. 1 Schematic of the blades

stress distribution cloud diagram also shows the surface pressure change of the stirring mechanism. Note that the pressure at the top of the blade is the highest and the pressure at the root is the lowest based on the different blade installation angles, which is consistent with the actual situation.

The speed of the mixer is 35 rpm under the five installation angles. Hence, the linear velocity distribution of the stirring mechanism is the same. The calculation result of the speed distribution is shown in Fig. 3, which indicates that the maximum speed is approximately 2 m/s. The speed direction is along the tangential direction of the imaginary circle radius position, where the speed value is located.

The line wear formula shows that obtaining the line wear rate of the stirring blade entails determining the pressure on the blade surface and the relative sliding speed between the stirring blade and the material. During the operation of the mixer, the relative sliding speed is related to the surface speed of the blade and its installation angle. Safety criteria indicate that only the cases where the relative sliding speed and surface pressure are the largest are analyzed. To establish a reference frame with the stirring blade, the instantaneous relative sliding speed V_{rel} of the material when it hits the stirring blade is analyzed (see schematic in Fig. 4). As shown in Fig. 4, V_{blade} is the instantaneous speed of the stirring blade and V_{surf} is the partial velocity of V_{blade} on the blade surface. Its direction should be opposite to the relative sliding speed, the values are equal, and α is the installation angle of the blade. Therefore, the relative sliding speed V_{rel} of the stirring blade and the material can be expressed as follows:

$$V_{rel} = -V_{surf} = V_{blade} \cdot \cos(90^\circ - \alpha) = V_{blade} \cdot \sin \alpha. \quad (4)$$

The relative sliding speeds can be calculated by substituting the blade installation angles $\alpha = 30^\circ$, 35° , 40° , 45° , and 50° into Formula (4) in sequence, thereby providing the following results: 1, 1.15, 1.29, 1.41, and 1.53 m/s, respectively.

By combining the obtained surface pressure values, a discrete numerical solution of the line wear rate of the stirring blade can be obtained. As an example, the pressure distribution of the No. 1 stirring blade is shown in Fig. 5. The line wear formula indicates that the line wear rate is proportional to the blade pressure. From the pressure distribution, the most severely worn area is mainly

Fig. 2 Cloud analysis of pressure at different angles

Fig. 3 Cloud speed distribution of the stirring mechanism

concentrated at the top of each stirring blade. The smaller the blade installation angle, the longer the high-pressure equivalence zone of the blade outer edge and the more well-distributed the pressure distribution. By comparing the pressure distribution diagrams, a clear pressure concentration is evident in the upper left corner of the blades at 45° and 50° , thereby indicating that this area is prone to severe wear.

The blade surface linear velocity and pressure distribution indicate that the maximum wear zone is at the outer edge of the blade's compressed surface (i.e., blade tip). On the basis of the safety criterion, the maximum wear rate can be calculated by taking the maximum pressure value into Formula (3). That is, the service life of the blade mainly depends on the maximum wear rate.

To compare the effects of the blade installation angle on blade life, the change rule of the maximum wear rate of the No. 1 blade under five angles was obtained by using Equation (3), shown in Table 1. Evidently, the relationship between the maximum line wear rate of the blade and installation angle is not a monotonous increase owing to the combined influence of relative sliding speed and surface pressure. The maximum line wear rate of the blade at

45° is as high as 2.78×10^{-9} m/s, while the blade line wear rate at 35° is the lowest at only 1.8×10^{-9} m/s.

2.4 Theoretical calculation of blade life

As shown in Table 1, the maximum line wear rate η also changes when the angle changes. By displaying the maximum line wear rate η in the form of service life, the performance of the workpiece will be considerably intuitive. Hence, the theoretical service life of the stirring blade is predicted on the bases of the relevant empirical assumptions and prediction analysis.

Hypothetical standards: (1) Blades should be replaced when the maximum wear area at the tip of the blade exceeds 50% (i.e., vertical wear $> 50\%$). (2) The No. 1 stirring blade, which has a thickness of 25 mm, is used as an example. The blade should be replaced when the wear thickness reaches 12.5 mm. The safety criterion indicates that the maximum line wear rate η is equal to 1.86×10^{-9} m/s, which is calculated by the mixer working time for 10 h per day, 6 days per week, according to Formula (5). The formula for calculating the theoretical life of the blade is as follows:

$$l = (D \times 50\% \times 10^{-3}) / (10 \times 6 \times 3600 \times \eta), \quad (5)$$

where l is the theoretical life days and D is the blade thickness.

By taking the corresponding parameters into Formula (5), the service life of the No. 1 stirring blade is calculated at approximately 187 days. The same method can be used to estimate the life of other blades. The theoretical life of the No. 1 blade under different installation angles is shown in Fig. 6. Note that the theoretical life of the blade with the lowest wear rate at 35° is the highest, which is approximately 192 days, and the theoretical life of the blade with the highest wear rate at 45° is the lowest, which is only 125 days. The other blades have the same theoretical life

Fig. 4 Schematic of the relative sliding between the mixing blade and the material

Fig. 5 Surface pressure distribution of the No. 1 mixing blade at different angles

Table 1 No. 1 mixing blade wear rate of the different installation angles

Angle (°)	Wear rate ($\times 10^{-9}$ m/s)
30	1.86
35	1.8
40	2.3
45	2.78
50	2.49

Fig. 6 Theoretical life of the No. 1 blade at different installation angles

calculation and regularities of distribution as the No. 1 blade. Thus, such calculation will no longer be repeated.

3 Selection of the optimal blade installation angle based on MATLAB angle selection

In the author's previous research [25], the average dispersion and power consumption of concrete under different blade installation angles of double-horizontal shafts mixer were obtained, shown in Table 2 and Table 3.

Curve fitting and mathematical modeling are processed using MATLAB to synthesize various performances, such as mixing effect, energy saving and environmental protection, and parts loss; and select the best blade installation angle, thereby providing a quantitative evaluation standard for selecting the blade installation angle.

According to the obtained simulation data, the scatter plots of the average dispersion, energy consumption, and wear rate of the prototype at the different installation angles can be drawn using the MATLAB curve fitting tool (shown in Fig. 7).

According to the fitted curve, the dispersion equation $f_1(x)$, energy consumption equation $f_2(x)$, and wear equation $f_3(x)$ are obtained as follows:

Table 2 Average dispersion at different angles

Angle (°)	Average dispersion
30	0.167
35	0.199
40	0.262
45	0.319
50	0.408

Table 3 Power consumption at different angles

Angle (°)	Energy consumption (kW)
30	22
35	21.5
40	21.2
45	20
50	19.2

(a) Average dispersion curve fitting

(b) Energy consumption fitting curve

(c) Wear rate fitting curve

Fig. 7 Fitted curves of the average dispersion, energy consumption, and wear rate

$$y_1 = f_1(x) = 2.505 \times 10^{-6}x^3 + 9.587 \times 10^{-6}x^2 - 0.001004x + 0.1198, \quad (6)$$

$$y_2 = f_2(x) = 0.0001333x^3 - 0.02029x^2 + 0.8295x + 11.74, \quad (7)$$

$$y_3 = f_3(x) = -0.0008867x^3 + 0.105x^2 - 4.026x + 52.06, \quad (8)$$

where x is the blade installation angle. The following performance evaluation function $F(x)$ is introduced according to Lagrange's theorem:

$$F(x) = \lambda_1 f_1(x) + \lambda_2 f_2(x) + \lambda_3 f_3(x), \quad (9)$$

where λ_1 , λ_2 , and λ_3 are the weight factors for y_1 , y_2 , and y_3 , respectively.

To unify the evaluation index, if we assume that the three weight factors used for the performance evaluation have the same impact on such an evaluation, then the index can be expressed as $\lambda_1 \Delta y_1 = \lambda_2 \Delta y_2 = \lambda_3 \Delta y_3$. If the evaluation coefficient is assumed to be $\lambda_1 = 1$, then the corresponding values are $\lambda_2 = 0.08607$ and $\lambda_3 = 0.181203$. In practical applications, users can personally define the values of λ_1 , λ_2 and λ_3 to obtain the best installation angle that meets their performance needs.

According to the performance requirements, the three major performance parameters are as small as possible. When $F(x)$ reaches the minimum value, the corresponding installation angle is the optimal one in the current study. The image and the maximum value of the evaluation function $F(x)$ are obtained through MATLAB mathematical processing and image functions (shown in Fig. 8).

The minimum value of $F(x)$ obtained using MATLAB is 2.46, and the corresponding x value is 31.81. The optimal installation angle is determined to be 31.8° under the given evaluation standard. According to the quantitative analysis shown in Fig. 8, the optimal installation angle interval is from 30° to 34°.

Fig. 8 Function image of the evaluation function

4 Conclusion

The theoretical maximum line wear rate η of the blades for the five blade installation angles was analyzed, and the theoretical life at five angles was calculated according to the corresponding conversion on the bases of the abrasion mechanism of the mixer and abrasive wear formula. Furthermore, the optimal installation angle and its range were determined.

1. The surface pressure distributions of the stirring mechanism under the five blade installation angles were obtained. The maximum pressure is distributed at the top of the pressure surface of the stirring blade. The maximum values at the installation angles of 30°, 35°, 40°, 45°, and 50° are 14,428.5, 13,123.6, 15,079.3, 16,147.5, and 13,538.4 Pa, respectively.
2. The line wear rate η of the stirring blade is proportional to the blades pressure. From the pressure distribution, the most severely worn area is mainly concentrated at the top of each stirring blade. The smaller the blade installation angle, the more evenly the pressure distribution. By comparing the pressure distribution diagrams, a clear pressure concentration exists at the upper left corner of the blades at 45° and 50°, thereby indicating that this area is prone to severe wear.
3. Under the combined influence of relative sliding speed and surface pressure, the relationship between the maximum line wear rate η of the blade and installation angle did not increase monotonously. The largest blade line wear rate η occurred at 45° at up to 2.78×10^{-9} m/s, and the smallest blade line wear rate η showed at 35° but only at 1.8×10^{-9} m/s. The theoretical life of the blade with the lowest wear rate at 35° was the highest at approximately 192 days, whereas that with the highest wear rate at 45° was the lowest at only 125 days.
4. Through curve fitting and mathematical modeling, the optimal theoretical installation angle of the stirring blade was determined to be 31.8° and the optimal installation interval was from 30° to 34°.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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