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SPEED CONTROL OF STEPWISE FEEDING AND DROPPING MATERIAL PREDICTION OF WEIGHING AND BATCHING PROCESS FOR MULTI-VARIETY MATERIALS

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Abstract. *How to control material feeding speed and guarantee batching accuracy are important issues in weighing and batching system. In this paper, by making an engineering reform of the reference curve of feeding speed proposed in our previous work, a multi-step feeding speed model is developed to facilitate industrial application. Furthermore, in a weighing and batching process of multi-variety materials, the height from the feeder outlet to the collecting box is always changing with the accumulation of different materials. To accommodate such changes, a dropping prediction model of multi-station cumulative weighing and batching process is developed. In the proposed dropping model, the effect of falling speed, material density, and height on the batching accuracy are taken into consideration so that a change in the variety of material and weighing height does not affect the accuracy of the prediction on the weight of the material remaining in air. The present control scheme has been successfully used in several real rubber production lines. Its effectiveness has been demonstrated through a comparison analysis of the new developed system with a conventional control system in a small-scale batching application.*

Keywords: Weighing and batching process, Multi-step feeding speed, Dropping prediction model

1. **Introduction.** Weighing and batching is the first and critical step in the production of many chemicals such as rubber, metallurgical, cash printing, oil ink [1-3]. To satisfy the technical requirement, weighing and batching process regulates the quantity of each material. It influences the operation of the following process and the quality of the product. Rubber production uses varieties of raw materials. Besides the main materials, there are many other essential ingredients such as sulfur or various additives to enhance the process-ability as well as the product properties. These compounding ingredients are usually used only in small quantities, even though they play fundamental roles in the production process. Any error in the batching process could cause a waste of raw materials, even a serious accident in production. In addition, the feeding speed influences the overall production efficiency significantly [4,5]. Consequently, keeping feeding speed

while ensuring batching accuracy has become an important issue in the weighing and batching system of rubber production.

In the early weighing and batching systems of rubber production, nearly all operations are carried out manually by trained or experienced operators [6]. However, it is not advisable for operators to control the weighing and batching process manually on site due to the following reasons: (1) Additives are of multi-varieties with different properties. Materials with same color and shape often have different physical and chemical characteristics. Any negligence of operator could make a mistake in materials ratio, causing serious loss. (2) High labor intensity while low production efficiency. (3) Due to human factors, the formula precision cannot be guaranteed. Stability and uniformity cannot be ensured for the products from different batches. (4) Most of the raw materials are in powder form and have low density, prone to stay in air and pollute the environment. Some of the ingredients are even detrimental to human health.

With the rapid development of industrial electronics technology, automatic control system was introduced into the weighing and batching process of rubber production. Conventional control systems generally employ dual speed control method to regulate the material feeding speed. The choice of the feeding speed level (fast and slow) is determined by weight measurement, whereas the material feeding speed is not fed back into PLC for direct control due to the speed intermittence. As a result, the system almost works in an open loop, where the final batching accuracy is only adjusted through shutting down the material feeding device when it approaches to a specific threshold value. Furthermore, this threshold value is an empirical value which must be adjusted carefully before being used to the engineering process. Generally, the specific threshold value has to be tuned when the environment or variety of material changes. On the other hand, the repetitive parameter tuning degrades the batching efficiency and makes the dual speed control method difficult to fulfill the practical requirement of multi-variety materials.

In practice, however, the batching process has severe nonlinearity, intermittence, time delay and disturbances caused by measurement noise, homogeneity of mass density, humidity and conveying viscosity [7]. Furthermore, with the change of material varieties due to different products or technical requirement, the characteristics of materials also change in the batching process. As a result, the actual material feeding speed often fluctuates even though it is regulated by the identical control operation with the same electromagnetic equipment. Therefore, the conformity of batching speed with the total material weight must be kept in an effective batching control system.

To reduce the complexity of operation and improve the batching accuracy, we have proposed a new mathematical reference model for controller parameter tuning and the parameter self-tuning approach in our previous study [8]. In the proposed approach, the material feeding speed and its acceleration are used to construct a cascade feedback control system, where an appropriate technical reference curve of feeding speed is designed by considering both material accuracy and response speed of the batching process. Even though the material variety changes, the parameter tuning can be performed through the reference model corresponding to the given technical requirement. However, there is a disadvantage with the technical speed curve proposed by literature [8]. The feeding speed is decreased at an exponential rate, making it difficult to implement by a PLC regulator. In such system a computer or an intelligent instrument based on the single-chip micro controller must be used as the master-control device to realize the exponential function of the feeding speed curve. Because PLC is more stable and reliable compared to a single-chip microcontroller, a PLC based feeding speed model is highly desired.

Furthermore, in the actual batching operation, when the materials are conveyed from the valve outlet to the collecting box, there will be a certain amount of materials remaining in conveying device or in air after shutting down the electromagnetic device or the valve to stop the batching process. These materials suspending in air will fall into the collecting box later and cause a difference between the weight of the actual feeding material and the weight displayed by the weighing equipment, which is called dropping. The influence of the dropping can be compensated by shutting down the valve at an appropriate time in advance. Nevertheless, threshold of shutting down is depended on the accurate prediction of the suspended material, which is an important issue in the weighing and batching process.

Even its importance as explained above, accurate dropping prediction has only been studied sparsely. And the researches are only specific to a single material batching [9,10] or multi-variety materials batching under a specific operational environment [11,12]. In reality, however, the dropping is a random variable, especially in a weighing and batching process of multi-variety materials. The height from the feeder outlet to the collecting box is always changing with the material accumulating. Furthermore, the feeding speed of every material is different. As a result, how to accurately predict the dropping in a multi-variety materials batching process has become a hard nut to crack.

High precision is needed for material concentration while efficiency is pursued in production. The issue has not been handled properly in the traditional prediction control method. Hence, we conduct present study with the objective of guaranteeing weighing precision and efficiency at the same time.

In our previous study we proposed the reference curve of feeding speed [8]. In this study we design a multi-step feeding speed model of the reference curve which can be realized easily by PLC. Furthermore, a dropping prediction model of multi-station accumulative weighing and batching process is established. Besides, because this proposed dropping model takes into consideration the effect of falling speed, density of the materials, and height on the batching accuracy, it can be used to predict the weight of the material remaining in air, which is not affected by the change of materials and weighing height. The schemes proposed in this paper have been successfully applied in real rubber production lines. The result shows that this model has improved the robustness and effectiveness in various industrial environments while ensuring the batching accuracy to fulfill the requirement of industrial production at the same time.

2. **The Multi-stages Feeding Speed Model.** The feeding speed curve proposed in literature [8] is shown in Figure 1, where the feeding speed shows two kinds of time dependences.

Initially, the feeding speed is maintained at a fixed speed V_0. Batching task is performed quickly with a high V_0, whereas the exact weight of batching materials is regulated at

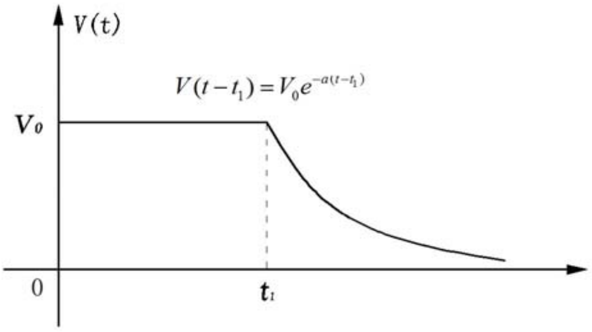

FIGURE 1. Feeding speed curve in literature [8]

the second step. When the amount of the material approaches the set value ($t > t_1$), the feeding speed is decreased from V_0 to a smaller velocity at an exponential rate to guarantee the feeding accuracy. However, this is difficult to implement by a PLC regulator because the measurement of material weight is only used for logic determination to switch feeding levels rather than a control variable to the feedback loop. As mentioned above, an intelligent instrument based on the single-chip micro controller is preferred as the master-control device. Unfortunately, application indicates that this intelligent instrument is not easily programmed and not sufficiently stable and reliable. To design a more robust and reliable control system, a novel multi-step feeding speed curve is proposed: the speed is decreased stepwise starting from V_0 through V_1, V_2, V_3 and V_4 instead of the exponential decrease model of the previous model. The multi-step feeding speed curve, as shown in Figure 2, can be realized easily by a PLC regulator.

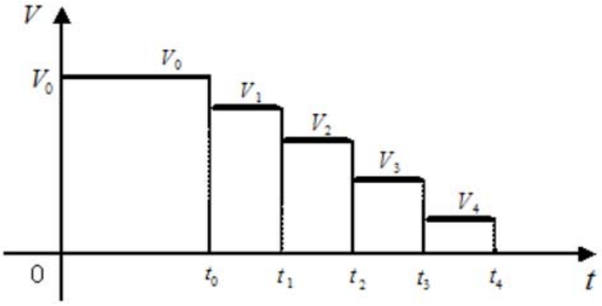

FIGURE 2. Multi-step feeding speed model

In a real rubber production, due to its unique features, the material weighing process should be limited within specified time and the weighing accuracy should be guaranteed. Furthermore, the weighing process is a cumulative process of the materials weight. The maximum setting value of a material weight W_i is generally no more than 10kg, and the weighing time is generally limited within 35 seconds.

Taking into consideration of the above constraint conditions, the feeding speeds at various steps are determined by the following principle. Based on Figure 2, the weighing precision is mainly controlled by the decelerating part of V_1, V_2, V_3 and V_4. However, for batching efficiency it is better to spend less time on decelerating under the condition of ensuring weighing precision. A minimum time (T) is needed for a specific feeding facility of a real operation to decelerate to one lower speed level, e.g., from V_2 to V_3. Value T depends on the type of the feeding facility. Vibrating feeder is used as an example in this study. According to the onsite experience, a minimum time $T = 3$ seconds is used.

For a given quantity of material and the overall batching time, one possible implementation is to set the feeding time for three seconds when the feeding speed is V_1, V_2, V_3, V_4, respectively. Hence, the total material mass obtained by the last four steps is about 1.110kg, and the remaining should be completed at the first stage with a speed of V_0. The initial feeding speed V_0 can be calculated using a backward induction method. Relationships between the feeding speed V and the material mass can be described as follows:

$$V = \begin{cases} V_0 & W_i \geq 1.110\text{kg} \\ 200\text{g/s} & W_i - 1.110\text{kg} \leq W_t \leq W_i - 0.510\text{kg} \\ 100\text{g/s} & W_i - 0.510\text{kg} \leq W_t \leq W_i - 0.210\text{kg} \\ 50\text{g/s} & W_i - 0.210\text{kg} \leq W_t \leq W_i - 0.060\text{kg} \\ 20\text{g/s} & W_i - 0.060\text{kg} \leq W_t \leq W_i \end{cases} \tag{1}$$

where W_i and W_t are the setting and real values of material weighing, respectively while V_0 is the initial feeding speed at the first step. In order to shorten the weighing time, V_0 is expected to be set as high as possible under the permitted operational condition. However, a too high V_0 will lead to a larger error when the setting mass of material is very low. So the ideal setting value of V_0 should be determined by considering the setting value of W_i. According to practical experience, a setting of 400g/s for the initial speed V_0 can achieve a better weighing result when W_i is 10kg. In addition, it can be seen obviously from Equation (1) that the initial feeding speed V_0 should be 200g/s when the material mass is 1.110kg. It is assumed that there is an approximately linear relationship between V_0 and the setting mass of material, which is as follows:

$$\frac{W_i - 10}{W_i - 1.11} = \frac{V_0 - 400}{V_0 - 200} \tag{2}$$

Thus the initial feeding speed V_0 can be obtained as follows:

$$V_0 = 22.47W_i + 175.28 \tag{3}$$

It means that the feeding speed for different steps depends on the material weight, which is convenient to be applied in actual batching operation.

In the modified control system, the feeding speed is still chosen as the control variable and the single loop control system works according to the theory as shown in Figure 3. The detailed controlling principle is illustrated in literature [8]. The mass measurement is fully used to determine the speed setting value online, and it plays the role of control similar to a cascade system. At the beginning stage, V_0 is fixed at a constant value determined by the setting mass, after that, with the accumulation of the material, the actual feeding speed varies according to Equation (1). In each step of the feeding speed, by using fuzzy digital control method, the actual feeding speed is regulated to fluctuate around the reference speed curve to guarantee the accuracy.

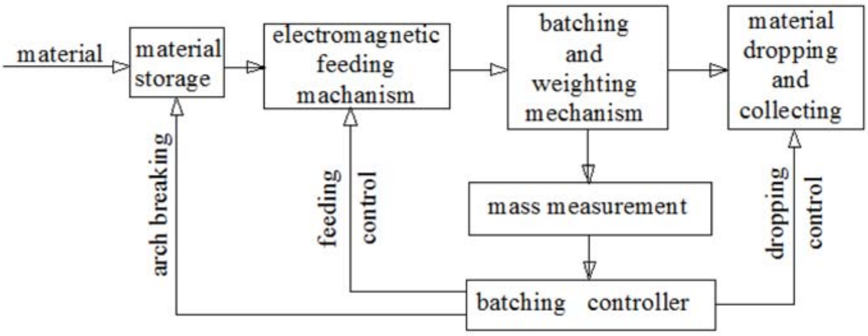

Figure 3. Diagram of the control system of batching system

3. Predictive Model of Dropping for Multi-station Batching Process.

3.1. **Multi-station weighing and batching system.** Products are manufactured by using several types of raw materials at a certain mixing ratio in ingredient processing, such as rubber, cement, food. This is especially apparent for the rubber products due to their performance depend largely on the various ingredients. Therefore, the varieties and quantities of material change with different products or technical requirement frequently. The main function of the weighing and batching process is to set right proportion for various raw materials in the exact amount to make the specified rubber product.

Figure 4. Schematic diagram of multi-station weighing and batching system

Figure 4 illustrates the detailed configuration of a multi-station batching system developed by MESNAC. Ltd. It has been put into use by many world famous tire enterprises, such as Michelin, Bridgestone, Double Coin Holdings. In the weighing and batching process, all the related materials belonging to a certain formula are arranged in a fixed order with each of them having its own weighing station which is primarily composed of feeder tank, feeder and electronic-weighing system. The multi-station batching system introduced in this work is consisted of 18 weighing stations and a total checking station. Each weighing station is responsible for a given variety of material and the general checking station is responsible for the batching accuracy of all the weighing materials. Stations are denoted as G: G_1G_2 ... G_i ... G_n $(i = 1, 2, \ldots, n)$, where i is the number of the positions. To reduce the complexity of operation and to control the system easily, the starting station G_1 and the general checking station G_{n+1} are addressed at the same position.

The detailed working process is as follows: a collecting bag is put into the collecting box by an operator at the starting point G_1. Then the collecting box is brought to the next work station G_2 by the transmission line. At the work station, a PLC will decide if the weighing of this kind of material needs to be done. When the following two conditions are both satisfied: one collecting bag in the collecting box and the material is one of the constituents of the formula, the material of this station will be injected into the collecting box and weighed. After the weighing process is finished, the collecting box goes to the next station G_3, which is shown in Figure 5. Otherwise, the collecting box goes to the station G_3 directly without the injection of the material. The procedure is carried out exactly the same way in the next work station until the last work station. At the last work

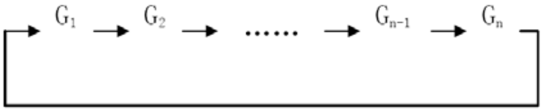

Figure 5. Material transmission line

station, after the collecting bag loaded with all the necessary raw materials is replaced by an empty collecting bag, the new weighing and batching process starts.

3.2. **Predictive model of dropping.** Accurate prediction of the dropping is vital to the batching precision. According to the analysis of the available literature, most researches focus on the dropping prediction in a single variety of material batching process. However, there are significant differences between the droppings formed in the multi-station batching process and the single material batching process except the first station of the multi-station. The main reason is that after the weighing in the former work station, there will be accumulated materials at a certain height. When going to the next weighing, the distance from the feeder outlet to the top of the accumulated materials in collecting box has changed so that there is varying dropping in every work station accordingly.

In addition, if the formula changes, the variety and amount of the constituent raw material change subsequently. Therefore, it is hard to ensure weighing accuracy by the conventional method of pre-closed control. To obtain a higher batching accuracy, at a given work station, a height of material accumulated in the collecting box should be calculated first according to the ingredient. Thereafter, based on the dropping height and the feeding speed when the feeding valve is shut down, a new method is proposed to estimate the mass of the dropping.

Actually, in the practical weighing and batching process, the materials, accumulated in the collecting box, are not evenly distributed but hill-like. To facilitate the calculation and control, it is assumed that the materials are evenly distributed in the collecting box in building the mathematical model. In addition, due to the fact that the cumulative weighing method is adopted in the multi-variety weighing and batching process, it is guaranteed that the distance from the outlet of feeder to the bottom of collecting box is a constant at each station.

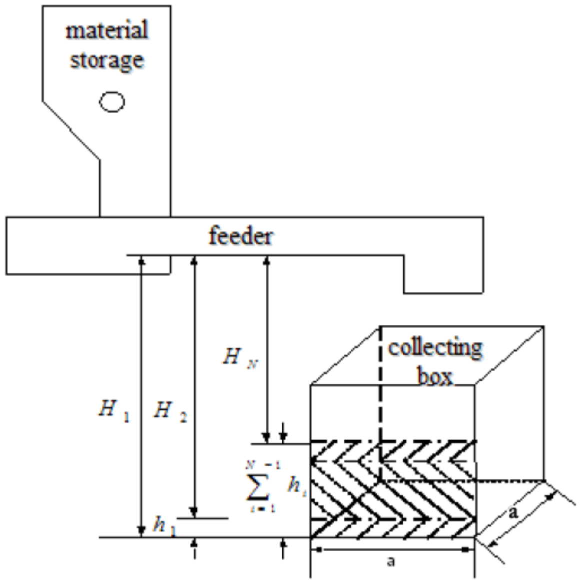

FIGURE 6. Schematic diagram of a weighing and batching station

As shown in Figure 6, H_1 denotes the height and S denotes the square of bottom in the collecting box while the other essential variables are listed as follows:

ρ_i – density of the i_{th} material (kg/m^3);

W_i – setting weight of the i_{th} material (kg);

t_i – time for the i_{th} material falling from the feeder outlet to the collecting box (S);

v_i – feeding speed of the i_{th} material when the feeding valve is shut down (m/s);
H_n – height from the feeder outlet to the top of material in the collecting box (m);
h_i – height of i_{th} material accumulated in the collecting box (m);
Q_i – volume of the i_{th} material accumulated in the collecting box (m^3).

It is assumed that the falling movement of material from the feeder outlet is of free-falling type. The time from the feeder outlet to the collecting box is given by:

$$t_i = \sqrt{2H_n/g} \tag{4}$$

Suppose the weighing speed is a constant, the mass of material remaining in air can be estimated by the following equation:

$$W_{pi} = v_i\sqrt{2H_n/g} \tag{5}$$

The volume of a material accumulated in the collecting box is calculated by:

$$\mathrm{Q}_i = S \times h_i = a^2 h_i \tag{6}$$

Then the mass of a material accumulated in the collecting box is

$$W_i = \rho_i \mathrm{Q}_i \tag{7}$$

From Equation (6) and Equation (7), the height of material accumulated in the collecting box can be obtained by following expression:

$$h_i = W_i/\rho_i a^2 \tag{8}$$

As a result, the height from the feeder outlet to the top of the material is given by:

$$H_n = H_1 - \sum_{i=1}^{n-1} h_i \tag{9}$$

where n is the number of material variety. Substituting H_n from Equation (9) into Equation (5) gives:

$$W_{pi} = v_i\sqrt{2\left(H_1 - \sum_{i=1}^{n-1} h_i\right)\Big/ g} \tag{10}$$

According to Equation (10), the mass of the material remaining in air can be estimated accurately even though the variety of material and weighing height change. The equation also offers the theoretical support to improve the weighing accuracy of multi-station batching system as well.

4. Practical Application.

To evaluate the proposed model, it was applied to a small quantity multi-station weighing and batching system of tire production factory. Using a given rubber ingredient of the tire production as a practical example, the effect of the present control system is investigated. Raw materials of the formula and their related parameters are shown in Table 1.

4.1. Determination of multi-step feeding speed.

As shown in Table 1, the required amount of every type of feeding material is different within the range of 1.93kg∼6.76kg. As discussed in Section 2, the maximum setting value of material weighing in this work is 6.76kg, below 10kg. In addition, because the weighing lasts for three seconds when the weighing speeds are V_1, V_2, V_3, V_4 and the corresponding weighing results are about 1.11kg, thus the V_0 of every type of material can be determined respectively using reverse induction method. In this work, if W_i is less than 5kg, V_0 is set to 300g/s and total weighing time is within 30 seconds. However, if W_i is greater than 5kg, V_0 is set to 400g/s and total weighing time is about 35 seconds.

TABLE 1. Materials and related parameters of a real batching operation

Sequence Number	**Materials**	**Required Quantity (kg)**	**Material density (kg/m^3)**	**Allowed error (kg)**
1	Accelerator TBBS	1.93	520	±0.01
2	Antiager 4020	2.83	770	±0.01
3	Octadecanoic Acid	5.80	690	±0.01
4	Microcrystalline Wax	3.86	580	±0.01
5	Zinc Oxide	6.76	620	±0.01
6	Total	21.18		±0.05

According to the above constraint conditions, the multi-step feeding speed of every raw material can be obtained easily. Due to space limit, discussions are only given for antioxidant 4020 and ZnO, and others can be carried out similarly. For the required antioxidant 4020 is 2.83kg, less than 5kg, its feeding speed is given by Equation (11).

$$\begin{cases} V_0 = 300\text{g/s} & W_i \geq 1.110\text{kg} \\ V_1 = 200\text{g/s} & W_i - 1.110\text{kg} \leq W_t \leq W_i - 0.510\text{kg} \\ V_2 = 100\text{g/s} & W_i - 0.510\text{kg} \leq W_t \leq W_i - 0.210\text{kg} \\ V_3 = 50\text{g/s} & W_i - 0.210\text{kg} \leq W_t \leq W_i - 0.060\text{kg} \\ V_4 = 20\text{g/s} & W_i - 0.060\text{kg} \leq W_t \leq W_i \end{cases} \tag{11}$$

For the required zinc oxide is 6.76kg, greater than 5kg, its feeding speed is given by Equation (12).

$$\begin{cases} V_0 = 400\text{g/s} & W_i \geq 1.110\text{kg} \\ V_1 = 200\text{g/s} & W_i - 1.110\text{kg} \leq W_t \leq W_i - 0.510\text{kg} \\ V_2 = 100\text{g/s} & W_i - 0.510\text{kg} \leq W_t \leq W_i - 0.210\text{kg} \\ V_3 = 50\text{g/s} & W_i - 0.210\text{kg} \leq W_t \leq W_i - 0.060\text{kg} \\ V_4 = 20\text{g/s} & W_i - 0.060\text{kg} \leq W_t \leq W_i \end{cases} \tag{12}$$

4.2. **Related parameters of the dropping model.** In the real multi-station batching system, parameters used in dropping prediction are decided by the following principles: the side length of the collecting box bottom is 0.5m, and the distance from the feeding outlet of each station to the bottom of feeding box is of same height, i.e., $H_1 = 0.7$m. On the other hand, due to many other factors such as moisture absorption and material density are likely to change in the real batching process, making it hard to estimate accurately. However, the change of density has little impact on the weighing accuracy so that the original density (offered by the manufacturer) is adopted in present investigation.

4.3. **Practical effect.** With the multi-station batching control system proposed in this paper, the components of a given rubber ingredient shown in Table 1 have been weighed five batches repeatedly. And the actual weighing results are listed in Table 2. In each cell of the table, the upper values are the weighing values while the lower ones are the measurement error. A positive measurement error indicates that measurement is higher than the real weight and is overestimated while a negative one means down-estimated. Figure 7 illustrates that the real change of the height of material accumulated in the collecting box by the multi-station cumulative weighing method.

For comparison, the weighing and batching process of the ingredient of rubber shown in Table 1 has been conducted in the same way by using the conventional control method, i.e., dual-speed feeding and pre-closed control method. The results are shown in Table 3.

Table 2 shows that, when the present control method based on the multi-step feeding speed and multi-station dropping prediction model is used, for all the materials, the

TABLE 2. Weighing results of the proposed control method

Material NO. Mass	Accelerant TBBS (**kg**)	Anti-aging agent 4020 (**kg**)	Stearic acid (**kg**)	Microcrystalline Wax (**kg**)	Zinc oxide (**kg**)	Total Amount (**kg**)
1	1.929	2.828	5.798	3.857	6.758	21.170
	-0.001	-0.002	-0.002	-0.003	-0.002	-0.010
2	1.931	2.827	5.799	3.859	6.757	21.173
	0.001	-0.003	-0.001	-0.001	-0.003	-0.007
3	1.933	2.831	5.798	3.858	6.758	21.178
	0.003	0.001	-0.002	-0.002	-0.002	-0.002
4	1.932	2.825	5.802	3.863	6.758	21.180
	0.002	-0.005	0.002	0.003	-0.002	0.000
5	1.929	2.834	5.802	3.858	6.763	21.186
	-0.001	0.004	0.002	-0.002	0.003	0.006

TABLE 3. Weighing results of the conventional control method

Material NO. Mass	Accelerant TBBS (**kg**)	Anti-aging agent 4020 (**kg**)	Stearic acid (**kg**)	Microcrystalline Wax (**kg**)	Zinc oxide (**kg**)	Total Amount (**kg**)
1	1.922	2.823	5.794	3.855	6.754	21.148
	-0.008	-0.007	-0.006	-0.005	-0.006	-0.032
2	1.923	2.826	5.792	3.855	6.751	21.147
	-0.007	-0.004	-0.008	-0.005	-0.009	-0.033
3	1.924	2.825	5.795	3.853	6.758	21.155
	-0.006	-0.005	-0.005	-0.007	-0.002	-0.025
4	1.925	2.821	5.791	3.855	6.750	21.142
	-0.005	-0.009	-0.009	-0.005	-0.010	-0.038
5	1.922	2.823	5.790	3.851	6.754	21.140
	-0.008	-0.007	-0.010	-0.009	-0.006	-0.040

FIGURE 7. Height variation of material pile in multi-variety material batching process

maximum error in 5 times of weighing is -0.005kg, much less than ± 0.01kg, the allowed weighing error. The maximum error in the overall weight is 0.01kg, much less than ± 0.05kg, the allowed weighing error for the overall weight. The result shows the reliability and precision of the proposed control system for application in rubber production process.

When the conventional control method is used, it can be seen form Table 3 that the maximum error for each material is -0.01kg, which is the same as the allowed weighing error (± 0.01kg). For the overall weight, the maximum error is 0.04kg while the average error is 0.0336kg. Both errors are smaller than ± 0.05kg, the allowed weighing error for overall weight. However, it is clear that even the error of the dual-speed model is within the allowed range, care needs to be taken because that it is close to the limit.

By observing and analyzing the data in Table 2 and Table 3, it is obvious that the weighing accuracy of the present control method is much higher than that of the conventional control method. For both the maximum weighing error and the average weighing error, the present control method gives much lower values than the conventional one.

5. Conclusion.

The main purpose of this work is to discuss control approaches for the weighing and batching process of multi-variety materials. By making an engineering reform of the reference curve of feeding speed developed in our previous study, a multi-step feeding speed model, which can be realized easily by PLC, is proposed. In addition, by considering the effect of falling speed, material density, and height of material accumulated on the batching accuracy, a dropping prediction model of the multi-station cumulative weighing and batching process has been developed. Based on the above work, we have developed a novel batching control system, and its effectiveness has been demonstrated by the comparison with the conventional control method in a small-scale batching implementation. From the experimental data and analysis, it is concluded that the present control method far outweighs the conventional dual-speed feeding and pre-closed control method. Furthermore, the present control method can also be applied to other manufacturing environments, such as chemical, food, textile, and cement industries.

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