July 3–7, 2017
Prague, Czech Republic
85th Annual Meeting
of International Commission on Large Dams

Proposing a fully automatic cementitious mix production system

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ABSTRACT

The authors have developed a continuous grading management system using a three-dimensional image processor capable of irradiating line laser light to CSG (cemented sand and gravel) materials on a belt conveyor, calculating the volumes of particles of different sizes from continuous image data obtained with a digital camera and determining particle size distribution in real time.

By using particle size distribution measurements obtained from the newly developed system in combination with moisture content measurements obtained with radioisotope moisture meters, the quantities of cement and water to be added to produce cemented fill materials can be controlled in real time.

This report deals with functions of a fully automatic cementitious mix production system consisting of these components.

1. INTRODUCTION

In recent years, productivity improvement and labour-saving efforts in construction have advanced the rationalization of design and construction processes, bringing about major changes in dam construction methods. Turning attention to the image processing technology which made a remarkable progress in recent years to the extent of being put to practical use in various applications, the authors have conducted a study to further improve the technology. Believing that grading measurement accuracy improvement and real time management are necessary for faster construction by the CSG method, the authors have developed a continuous grading management system using a three-dimensional image processing system, which is a completely new type of grading management system using an image processing technique called the optical cutting method. By combining particle size distributions obtained by use of the newly developed system and moisture content measurements obtained with nuclear gauges, adjustments can be made in real time of the quantities of cement and water to be added in producing a cement-bound sand and gravel mixture. This paper proposes a system and methodology of this fully automatic cement mixing system.

2. GRADING MEASUREMENT SYSTEM

2.1 Background of development

The embankment material called CSG, which is widely used for the construction of the main structures of dams and coastal levees, is produced by mixing locally available rocky material (CSG material) with cement and water without making grading adjustments or washing. Grading control is important in order to attain the required strength of CSG mixes. Sieve analysis, therefore, is carried out manually every one or two hours to check whether the particle size of CSG material is within the diamond-shaped area on the strength–unit water content chart. Manual sieve analysis, however, is labour-consuming and requires time-consuming measurements. There was a need, therefore, for a real-time grading control technique that is easy to perform and makes it possible to deal with abrupt changes in particle size.

2.2 Technological challenges in 2D image processing revealed by preliminary experiment

Techniques for CSG material grading control through two-dimensional image processing using digital camera images (Fujisaki et al.2013, Eda et al.2014) have already been developed for real-time measurement of changes in particle size distribution. The authors fabricated a 90-centimeter-wide white belt conveyor, captured images of CSG material on the belt conveyor with a digital camera, and made particle size measurements by use of image processing. This experiment revealed the following technological challenges:

- Particle size measurement through image processing requires eliminating overlapping and sticking together of particles to clarify the contours of individual particles. It is possible to clarify the contours of individual particles sticking together by use of image processing (e.g. edge enhancement by binarization with a Laplacian filter, wavelet transform). That method, however, was too burdensome in terms of image processing time, and the method failed to meet edge enhancement needs depending on the way the particles stick together.
- Two-dimensional images are easily affected by defocus and dark areas. Creating a desirable image-capturing environment, therefore, is difficult.

In view of these results, the authors decided to develop a method for mechanically dispersing the CSG material sample put onto the belt conveyor and an image-capturing device and an image-capturing method that are relatively free from the influence of the image-capturing environment.

2.3 Development of new system

2.3.1 Pre-imaging preparation

In order to select a method for mechanically dispersing the CSG material sample on the belt conveyor, experimental systems for the method of freely dropping the sample onto the belt conveyor (Case 1) and the method of using a combination of two material handling devices that have different speeds (Case 2) were fabricated for verification testing. For both methods, a digital camera system was used for image capturing. In Case 1, when the sample was dropped onto a belt conveyor, the depth of field posed problems such as overlapping of particles and difficulty in focusing. In Case 2, the sample extracted by a belt feeder (lower speed) was transferred onto a higher-speed belt conveyor for the purpose of dispersion. As it turned out, the sample that fell freely onto the belt conveyor from the belt feeder dispersed more or less uniformly, but 5millimeter or smaller particles could not be identified. In order to achieve 100% matching between captured images and actual sample particles while performing continuous image capturing, it was necessary to connect together the obtained images. The technology for doing it, however, was not available.

2.3.2 Image-capturing system

To solve the problems mentioned above, the authors thought of using a three-dimensional line laser camera system capable of identifying individual objects as three-dimensional information and detecting objects that differ in shape from normal objects as in the completion inspection of automotive parts. The camera irradiates laser light to an object and captures images of the laser light (profile) along the changing contour of the object with a diagonally positioned camera to obtain three-dimensional surface contour data (optical cutting method). Because combining this camera with image processing technology enables continuous acquisition of three-dimensional surface profile data and volume calculation of a given portion of the object being inspected, the authors thought that CSG material particles can be measured in real time. By using the apparatus used for the preliminary experiment, therefore, samples having similar particle size distributions were dispersed and placed differently, and their images were captured with the 3D line laser camera. Then, the ratios between particles of different sizes were compared in terms of projected area (Figure 1). The comparison showed that the difference among three cases of particle size measurement was greater than 1.54% (Table 1). From this, the authors concluded that the measurement system excels in reproducibility.

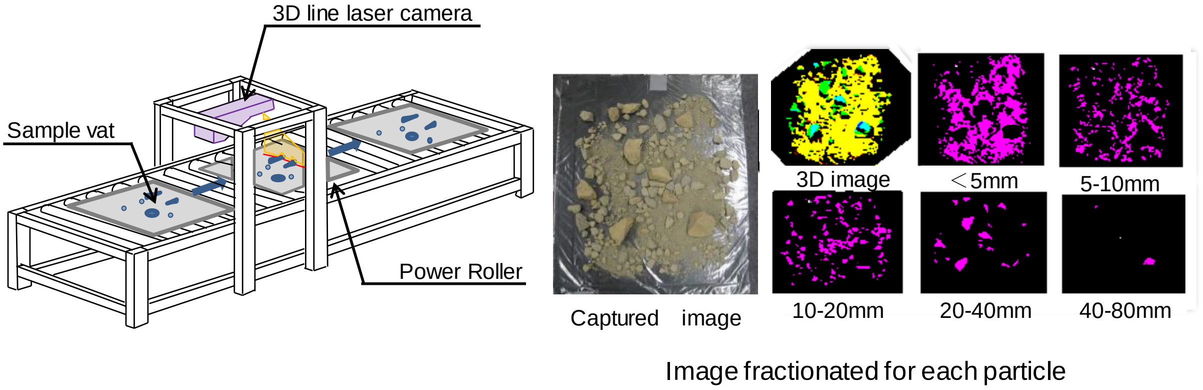


Figure 1. Preliminary experiment apparatus using 3D line laser camera

Table 1. Results of preliminary experiment using 3D line laser camera

Particle size	<5mm	5-10mm	10-20mm	20-40mm	40-80mm
Case1	24.17	10.52	8.75	4.06	0.24
Case2	25.71	10.93	8.59	3.39	0.27
Case3	24.50	10.66	8.83	3.74	0.42
max-min(%)	1.54	0.41	0.24	0.67	0.18

2.4 System configuration

On the basis of the results of the preliminary experiment, a new particle size measurement system (Figure 2) was developed. In the system, rocky material (CSG material) is put into the feeding hopper, and then the material is dispersed on the belt feeder and the belt conveyor. Images of the material thus dispersed on the belt conveyor are captured with the 3D line laser camera, and then image processing is performed.

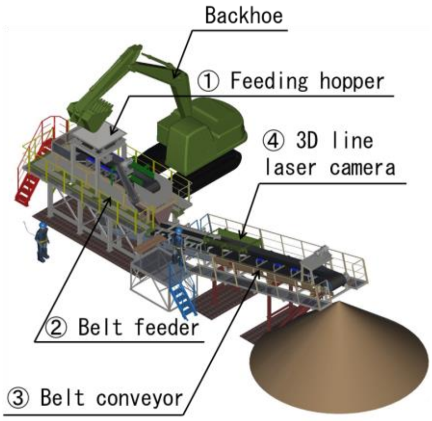


Figure 2. Grading measurement system

2.4.1 Dispersion system consisting of belt feeder and belt conveyor

The speed difference between the belt feeder and the belt conveyor was determined by evaluating the dispersing effects of several speed differences. The speeds of the belt feeder and the belt conveyor thus determined were 1 m/min and 75 m/min, respectively. In theory, the CSG material put onto the belt feeder to form a 10-centimeter-thick layer is dispersed on the belt conveyor, forming a 1.3-millimeter-thick layer.

2.4.2 3D line laser camera

The 3D line laser camera used allows changing the number of profiles that can be acquired per second. Comparison of processing speed and accuracy was made in advance in several cases, and it was decided to go with the data acquisition rate of 800 profiles per second. This means that if the speed of the belt conveyor is 75 m/min, profile data are acquired at intervals of 0.16 cm (Figure 3). The camera was placed in a darkroom to make laser light, which is difficult to see under sunlight, clearly visible and prevent laser light distortion due to water droplets sticking to the light source. In order to prevent defocusing due to reference height fluctuation caused by belt conveyor vibration, the camera and the belt conveyor were separated so that vibration does not propagate to the camera. In addition, impact bars were installed to the belt conveyor surface to keep the distance between the belt conveyor surface and the camera constant.

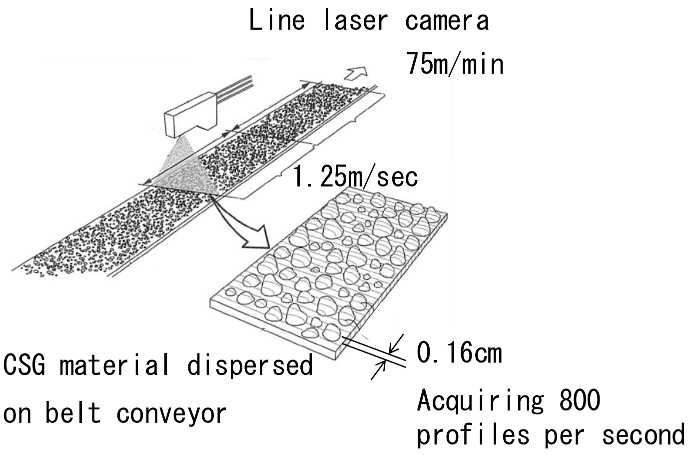


Figure 3. Optical cutting method using line laser camera

3. PERFORMANCE VERIFICATION OF PARTICLE SIZE MEASUREMENT SYSTEM

3.1 Material used

The material used for the system performance verification was the same as the CSG material used for the landslide control works at Asakawa Dam. The material was smaller-than-80-mm andesite (Neogene volcanic rock) grains prepared by removing 80 mm or larger grains by use of a mobile screen.

3.2 Performance verification method

The CSG material sample (about 90 kg) was put into the feeding hopper by use of a backhoe. The CSG material put onto the belt feeder was dropped onto and dispersed over the belt conveyor surface. Images of the CSG material on the belt conveyor were then shot with the 3D line laser camera for about one minute at an image acquisition rate of 800 profiles per second. The entire volume of the CSG material thus discharged from the system was subjected to sieve analysis (simple method). To evaluate the influence of differences in the condition of the CSG material stored at the stockyard, samples were taken from different locations and on different days: 10 samples were taken on each day, and a total of 30 samples were taken over a period of three days.

The image data thus obtained were converted, profile by profile, into two-dimensional data, and the cross-sectional area was measured for each height from the belt conveyor surface (Figure 4). Then, volume was calculated by mathematically integrating the data corresponding to about one minute (i.e. data for the entire volume of CSG material sample). The value obtained by multiplying the volume ratio thus obtained by the surface-dry density for each particle size class (Table 2) was taken as the weight ratio (hereinafter referred to as the "image weight ratio").

Thus, system performance was verified by comparing the weight ratio determined through image processing (image weight ratio) and the simple sieve analysis result (weight ratio).

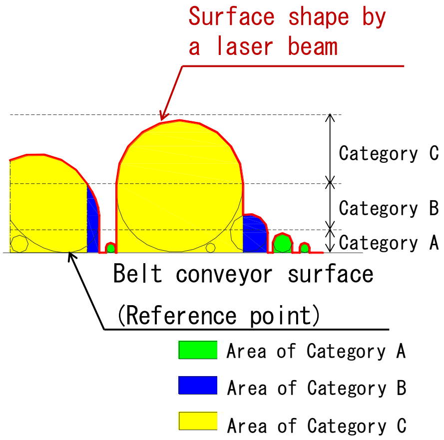


Figure 4. Profile data classification in image processing

Table 2. Surface-dry density by particle size

Particle size（mm）	80～40	40～20	20～10	10～5	5～0
Surface dry density (g/cm^3)	2.62	2.58	2.57	2.55	2.42

3.3 Performance verification results

Figure 5 compares the image weight ratio and the weight ratio determined through sieve analysis. For the purpose of comparison, the height classes (height from the belt conveyor) used for volume ratio calculation in the image weight ratio calculation process were determined according to the sieve opening sizes (5, 10, 20 and 40 mm) used in sieve analysis. The average of the values obtained on each day (from 10 samples) was taken as the Case 1, Case 2 or Case 3 value, and the values thus obtained were used for comparison.

The comparison revealed that the particle size distribution curves obtained by the two different methods differ significantly, and the particle size distribution based on the image weight ratio tended to indicate smaller particle sizes.

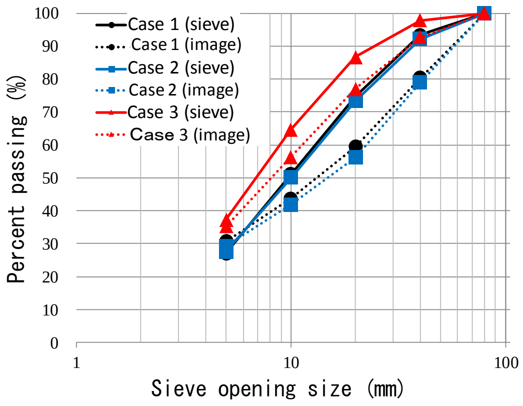


Figure 5. Comparison between image weight ratio and sieve analysis weight ratio determined by sieve analysis

3.4 Discussion on experimental results

It was suspected that the differences in particle size distribution between the image weight ratio and the weight ratio determined through sieve analysis were caused not only by density differences among different particle sizes but also by the oblate of particles. Because images of the particles on the belt conveyor were captured after the particles moved into stable positions, it was thought that the assumption that height from the belt conveyor surface is equal to particle size led to the particle size differences. In the case of an oblate particle as shown in Figure 6, the intermediate edge length b of the circumscribed rectangular parallelepiped was taken to be the particle size in the sieve analysis, while in the proposed system the shortest edge length c was taken to be the particle size. That, it was thought, might have caused the particle size differences.

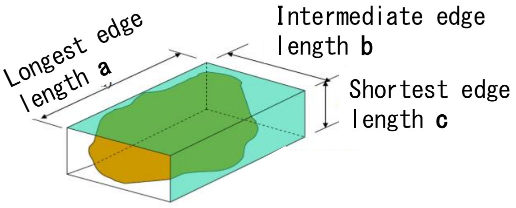


Figure 6. Circumscribed rectangular parallelepiped

3.5 Making corrections

3.5.1 Image weight ratio correction based on optimum thresholds

In view of the discussion described above, it was decided to make corrections using particle size classification criteria (hereinafter referred to as "optimum thresholds") that make the relation "image weight ratio = weight ratio base on sieve analysis" hold true by following the steps described below.

Step 1: Determine the cross-sectional area for each profile data set in each size class by varying threshold in steps of 0.5 mm (Figure 7) and calculate the volume ratio.

Step 2: Compare the image weight ratio determined by multiplying the volume ratio for each sample by the surface-dry density corresponding to the particle size with the weight ratio determined through sieve analysis and select a threshold (in 0.5 mm steps) that makes the two weight ratios the same or similar.

Step 3: Draw a histogram for the thresholds selected and take the mode as the optimum threshold. If there are two or more modes, then take the one closer to the median as the optimum threshold (an example for 5–10 mm shown in Figure 8).

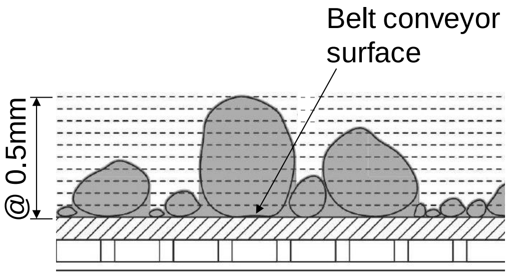


Figure 7. Steps for optimum threshold search

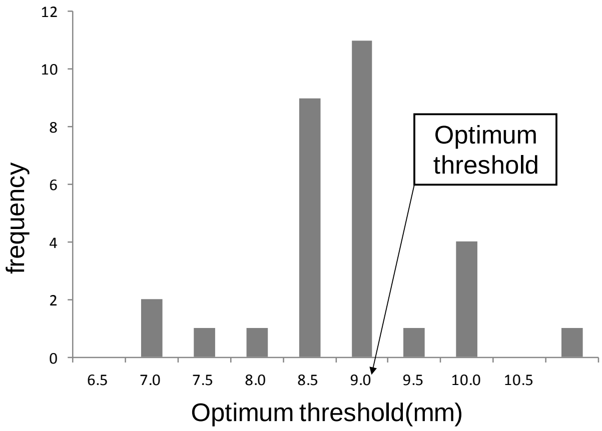


Figure 8. Optimum threshold histogram (5–10 mm)

Table 3 shows the sieve opening sizes used in the sieve analysis and the optimum thresholds for image processing calculated from the histogram. While the sieve opening sizes used in the sieve analysis were 0–5–10–20–40–80 mm, the optimum thresholds used in the performance verification experiment were 0–5.5–9.0–14–27–80 mm.

Table 3. Comparison between sieve opening sizes and optimum thresholds

	Sieve opening sizes and optimum thresholds (mm)					
Sieve analysis weight ratio	0.0	5.0	10.0	20.0	40.0	80.0
Image weight ratio	0.0	5.5	9.0	14.0	27.0	80.0

3.5.2 Comparison of image weight ratio using optimum thresholds and weight ratio determined through sieve analysis

By using the optimum thresholds shown in Table 3, the image weight ratio was recalculated from the three-dimensional image data, and the results were compared with the weight ratios determined through sieve analysis (Figure 9). Although the image weight ratio curves and the sieve analysis weight ratio curves show significant differences in Figure 5, the differences have now been made smaller by using the optimum thresholds. In all cases, the difference between the two weight ratios (Figure 10) is mostly within ±5%.

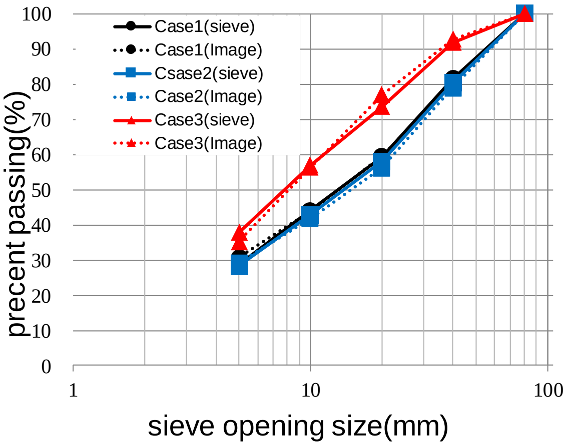


Figure 9. Image weight ratio vs. sieve analysis weight ratio(case average)

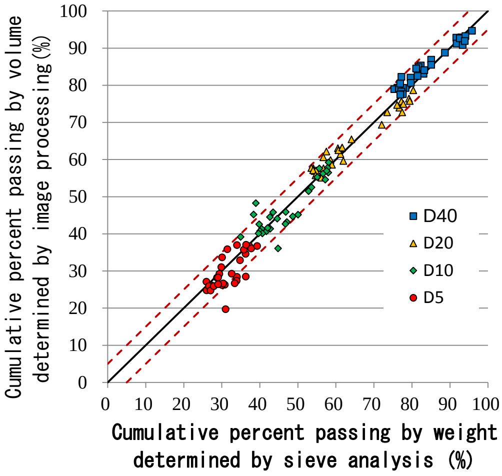


Figure 10. Image weight ratio vs. sieve analysis weight ratio(each)

4. PROPOSED FULLY AUTMATIC CEMENNT-BOUND MIX PRODUCTION SYSTEM

4.1 Approach to full automation

In connection with the construction of structures by use of cementitious binder, it is generally known that cementitious binder and earth material (particle size distribution) are related as shown in Figure 11. As shown, if the cement content remains unchanged, unconfined compressive strength increases with the coarse grain content and decreases as the fine grain content increases.

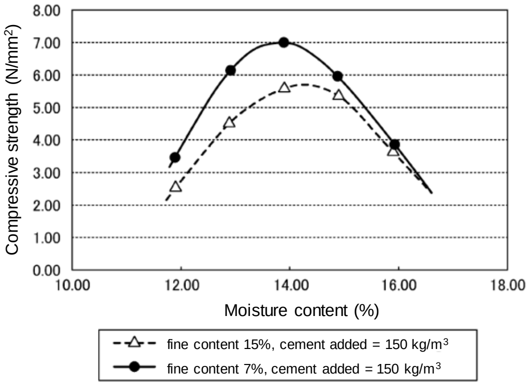


Figure 11. Effect of grading on relationship between moisture content and compressive strength (Sabo and Landslide Technical Center)

This is thought to indicate, therefore, that if the real-time grading measurement system described in the preceding section is used, cement-bound material with the required strength can be produced with high accuracy in a rational and efficient manner by use of a minimum amount of cement by adjusting the quantity of cement added to the mixture being produced according to the measurement results.

4.2 Challenges for full automation

4.2.1 Influence of grading on strength distribution of cement mixtures

In cases where the quantity of cement added to the mixture is changed according to real-time measurement results, whether the cement mixture produced meets the minimum compressive strength requirements or not is directly affected by the accuracy of grading measurement results.

4.2.2 Moisture content measurement error

The moisture content of the material used can be measured in real time by a radioisotope (RI) based method. Even this method, however, is subject to measurement error. During the landslide control work carried out at Asakawa Dam, measurement errors were within ±1% (Figure 12).

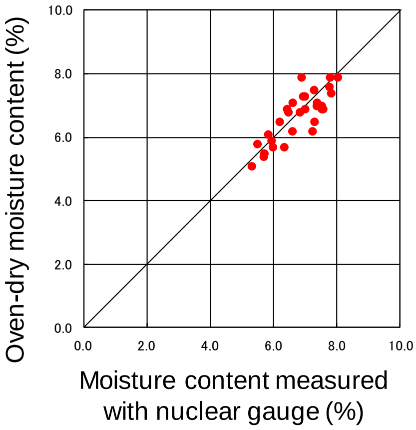


Figure 12. Correlation between moisture content measured with nuclear gauge and oven-dry moisture content

4.3 Structure of fully automatic production system

In order to fully automate cement mix production, the system shown below has been developed as a state-of-the-art mixing plant. Figure 13 shows the basic flow of the system. Figure 14 shows a plan view of the system.

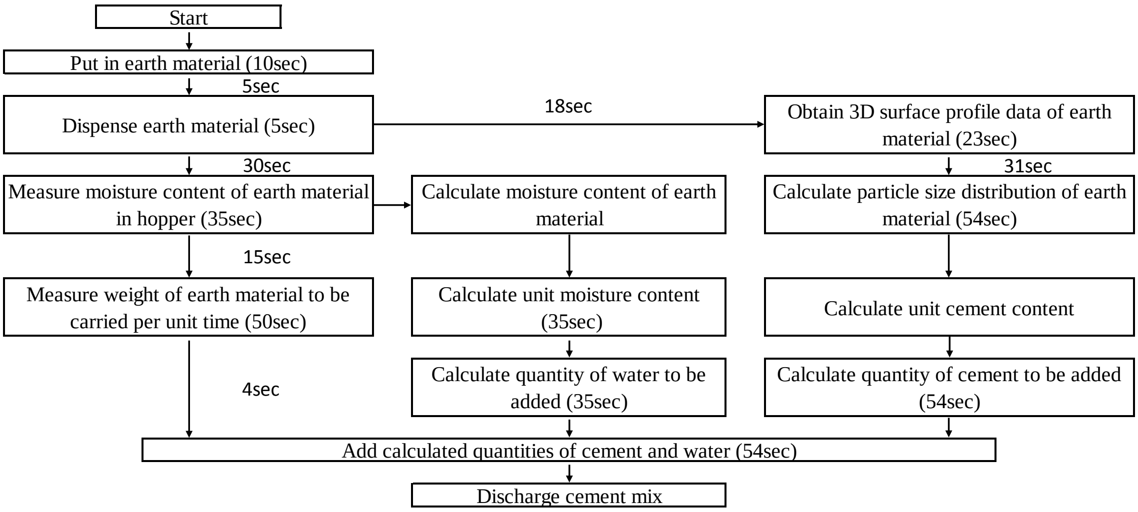
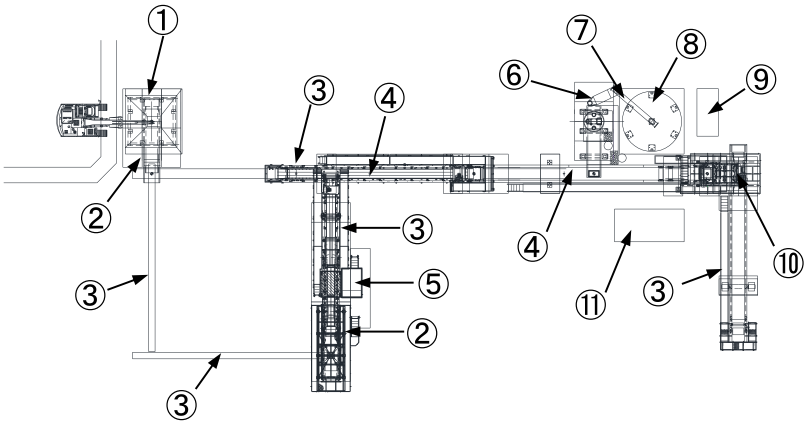


Figure13. Flowchart for fully automatic production system



①	Feeding hopper
②	Belt feeder
③	Belt conveyor
④	Belt scale
⑤	Camera dark room
⑥	Bucket elevator
⑦	Screw conveyor
⑧	Cement silo
⑨	Water tank
⑩	2 Axis mixer
⑪	Operation room

Figure 14. Structure of fully automatic production system (plan view)

4.4 Construction management method of fully automatic production system

4.4.1 Grading control

The grading measurement system measures with a continuous grading control system using a three-dimensional image processing system utilizing the optical cutting method of image processing. Earth material put into the hopper of the mixing device is transferred from the dispensing feeder to the splitting chute and fed to the grading analysis system line. The feed rate is adjusted by means of the cut gate so that earth particles do not get piled up on the high-speed belt conveyor. In grading measurement, if the maximum grain size is 80 mm, it is necessary to measure about 100 kg. If the belt conveyor is 900 mm wide, 100 kg is reached in about 30 seconds, and the particle size distribution measured is displayed one second later.

The material used for particle size measurement is brought back to the mixing device by a belt conveyor system consisting of conveyor units arranged in a square pattern.

4.4.2 Moisture content control

The moisture content of the earth material put into the mixing device is measured with nuclear (radioisotope) moisture and density gauges installed in the hopper. After subtracting the absorptivity determined in advance from the moisture content, the surface moisture content is calculated. Then, the quantity of water that needs to be added to attain the required water content is calculated.

4.4.3 Cement and water content control

For the purpose of cement and water content control, weight measurements are made with the belt conveyor's scale before earth material is put into the mixing device. Weight measurement is made continuously, and required quantities of cement and water are added to the material put into the mixing device (mixer). The quantity of cement to be added is adjusted in real time according to grading measurement results, and the quantity of water to be added is also adjusted in real time according to nuclear moisture and density gauge measurement results.

4.4.4 Overall system time lag adjustment

The quantities of cement and water to be added are calculated in real time according to grading measurement results, moisture content measurement results and material weight measurement results. The required quantity of cement or water, however, must be added to the same batch of material whose properties were measured. It is therefore necessary to adjust the length of time of discharge from the receiving hopper to allow for the time lag associated with measurement.

The material whose moisture content was measured is discharged from the hopper, and the same material must pass through the grading measurement system and the weight measurement system and be put into the mixer at the correct timing (refer to the timing shown in Figure 13). Although the samples for particle size testing are put into the mixer in advance, their quantities are negligibly small.

However, even if the material to which measurement results correspond can be identified through time adjustment, using the real-time measurement results as they are to determine the quantity of cement or water to be added may result in a greater range of fluctuations.

It is thought, therefore, that the best way to do is to use the moving average approach. An example of such a method is to calculate a five-minute average and determine the quantity of cement or water to be added during the next one-minute period. (Figure 15)

Control methods associated with such measurement time adjustments and moving averages should be determined in view of the results of strength tests conducted in advance.

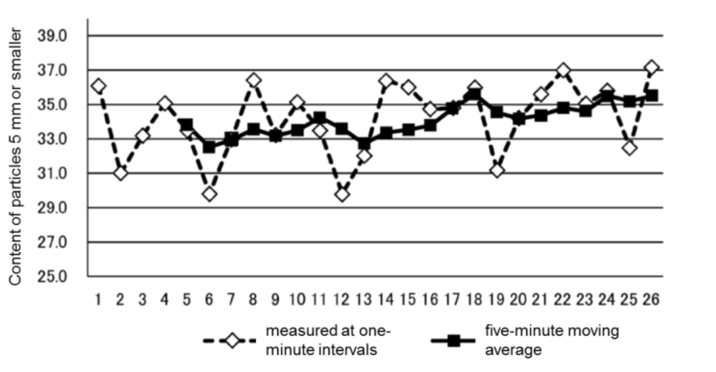


Figure 15. Moving average calculation in grading test (example)

5. CONCLUSION

The knowledge gained in connection with the performance verification experiment of the continuous grading management system and the proposed fully automatic production system can be summarized as follows:

- Highly accurate measurement results can be obtained by a simple method using the difference in speed between a belt feeder and a belt conveyor.
- While two-dimensional image analysis requires time-consuming image processing for edge enhancement, the newly developed system makes it possible to obtain results in several seconds and check on particle size distribution in real time.
- By analysing the entire volume of the material put into the measuring device, the newly developed system performs measurement with consistent accuracy, free from non-representative samples and variability problems due to the quantity of the material measured, so as to achieve 100% matching between the material measured and measurement results and enhance measuring accuracy. Although the largest particle size of the material used in the experiment was 80 mm, earth material having a maximum particle size of up to 150 mm can be measured with a single camera.
- By performing calibration (comparison of the image weight ratio and the weight ratio determined through sieve analysis) using about 30 samples and setting optimum thresholds, differences in measurement results between the image weight ratio and the sieve analysis weight ratio can be kept within about ±5%.
- Continuous sampling makes near-real-time measurement of particle size distribution possible. The authors believe that incorporating the grading measurement device and the nuclear moisture and density gauge system mentioned in this paper is a major step toward the realization of a technology to regulate and adjust the quantity of cementitious binder added to the cement mixture being produced to attain the required strength of the mixture by measuring grading and moisture content.

6. TASKS AHEAD

With the technique developed in this study, it is now possible to measure grading in real time easily and accurately by using a commercially available camera and general-purpose equipment. It is believed that the technique can be applied to other types of work that uses earth material (e.g. cemented material dams). The authors believe that if the proposed fully automatic cement mixture production system is made a reality, it is possible to produce cement mixtures with consistent accuracy and stable quality. Furthermore, since the quantity of cement used can be reduced, carbon dioxide emissions and cost can also be reduced.

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