Automated Measurement and Estimation of Concrete Strength by Mobile Robot with Small-sized Grinding Drill

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ABSTRACT

This paper describes on the estimation method of compressed strength for the concrete construction such as highway roads, large bridges, dam and tunnel, and the autonomous mobile robot with that the small sized grinding drill. In the control of a drill feed rate using the torque motor, the feed rate is expected to be a constant as the torque depending on load. However, the feed rate of drill was found to change for concrete strength and to be the approximately constant to concrete strength when the drill load was up to the setting value of torque. As a result of perforating experiment, the comparison of the concrete strength and drill feed rate was able to similar by inversed power curve. Installing this inspection system on a mobile robot, we got the possibility that automated estimation of concrete strength was carried out easily at construction site. Measuring the feed rate by this drill, the concrete strength was expected to estimate practically.
Keywords: Estimation method, Concrete strength, Grinding drill, Torque motor control, Mobile robot

1 Introduction

Most of infrastructures for civil engineering (highway road, bridge, tunnel, etc.) built around the urban region in high-growth era of 1970-1990 have begun to reach the life and it has been the time when large-scale repair and renewal, rebuilding are necessary. Especially, as there is the case which the concrete strength is decreased remarkably by aged deterioration as well as salt damage or neutralization, immediate improvement of the damage is demanded [1]. As concrete structure needing such improvement, firstly the establishment of the concrete strength estimate method that can judge the degree of the deterioration objectively and the system which the inspection is perform instantly is requested.

As the conventional method of estimation for the concrete strength, the following method is reported;
(1) Compressed strength examination to small core pulled out existed structure
(2) Reacted strength examination hitting the concrete surface by test hammer [2], and measuring method between spread speed of elastic wave and reflected time.
(3)The method measuring the elastic speed into the concrete by giving ultrasonic wave

However, when using the compressed strength device, it costs enormous time and expense for core collection and strength examination. Though hitting method is low price and easy, it is limited to a strength measurement of the concrete surface neighborhood. In the case of ultrasonic wave, the strength value is known to influence the mix proportion of coarse aggregate of concrete. Therefore, more ease and speedy detection methods demanded at the construction site.

In a past study, one of the authors has devised a method to estimate concrete strength using a small size grinding drill from the relation perforating speed of the hole and pushing power by compressed air. As for the air pressure, the handling is very simple, but the measurement precision to absorb the change on the cutting condition is not so high. And, the cutting speed is decided by a compressed air power to set, it is difficult to choose appropriate cutting speed when the concrete strength is unknown indeed.

In this study, the drill system with a torque motor and automated measurement by mobile robot, the inspection method which the concrete strength is estimated from change of the perforating speed, are mainly examined. Generally, in the control using the torque motor, the torque corresponding to the load is outputted and the perforating speed is expected to become constant regardless the concrete strength. However, in the case of high strength concrete, as the load more than a set torque may act on the drill, the perforating speed decrease to the strength of concrete material and it is found to be about constant individually. As the proposed drill is compact size and the short term work was performed easily, this system is suitable to the site estimation of concrete strength.

In this report, as basic study and development technology, the main drill system and its perforation principle, the plan of automated measurement by mobile robot, the result of perforating experiment and estimation, are explained.

2 Composition of Drill Measurement System and Application Plan

2.1 Outline of Grinding Drill

The drill system using the experiment is shown in Figure 1. The System was mainly constructed from the perforation drill, slide block mechanism, water circulation device and vacuum pump. This drill was a grinding drill of the small size diameter of 15.5mm that installs the sintered alloy bit inlaid diamond particles in the shank top, and the deep hole of 250 mm a time could be perforated while grinding a concrete surface in the high velocity rotation.

The drill body was fixed to slide block composed from rack and pinion, and moved up and down along the pole base. The circulation device e inside of the base was adsorbed with a vacuum pump, and the test piece and the drill base could be fixed. When perforating with a water, cooling and lubricating of the bit and discharge of shaving of concrete was done.

2.2 Outline of Mobile Robot System

In order to enable automatic perforating and detecting the concrete strength, the mobile robot that remodelled Omni-wheel vehicle was produced with the drill body [3]. The outline of mobile robot is indicated Figure 2. The perforation drill is fixed to the slide block of a robot comprised of a rack and a pinion, and the drill is automatically moved up and down. Introducing a wireless control, the strength inspection of a concrete structure in the disaster region to which the worker can't go may be achieved.

2.2.1 Application Plans (1)

The developed mobile robot was planned to apply to the disaster sites such a large bridge, building dam made of concrete materials as shown in Figure 3. In these cases, because there is danger of the collapse, as for such concrete structure, the worker cannot approach these sites. So, to inspect the concrete strength, the introductions of the robots with detection device by remote operation are effective. As the mobile robot was able to move in all directions and to rotate in the angle of 360 degree, the robot can move to desire positions according to operation and the strength of desire points are estimated.

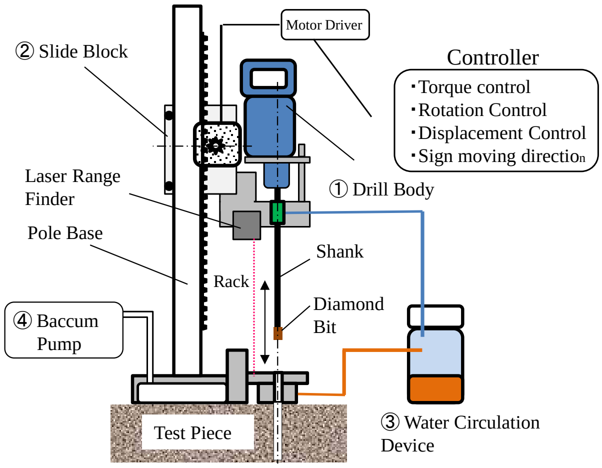

Figure 1 Outline of grinding drill system for concrete strength test

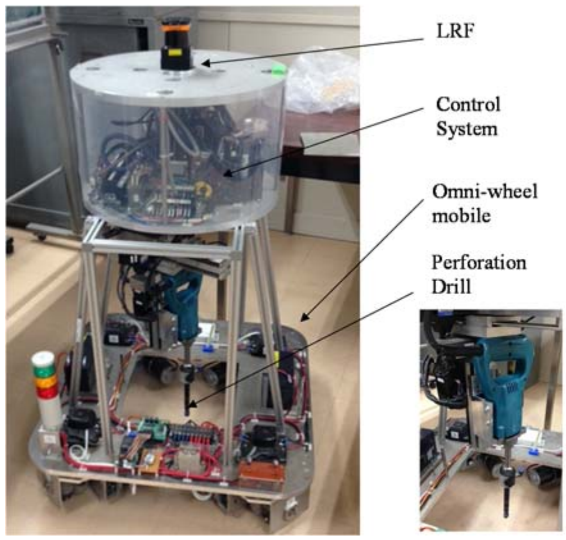

Figure 2 Mobile Robot installed on grinding drill

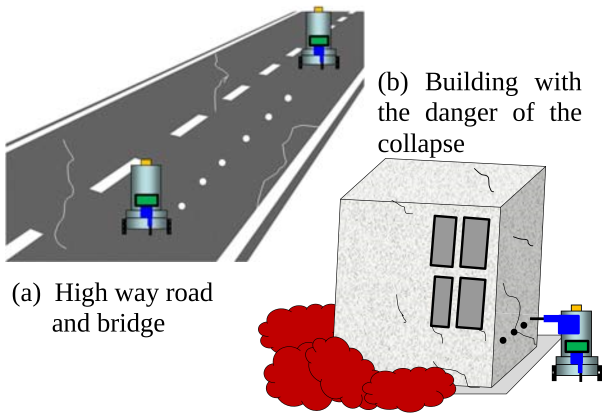

Figure 3 Application plans of disaster sites using mobile robot with grinding drill

2.2.2 Application Plans (2)

The drill system and control units separating from the mobile robot, it can be set to the other mobile mechanism. For an example, we will plan to develop the tunnel inspection mechanism for the inner wall strength by this drill system to prevent a miserable past tunnel accident in Japan. The outline of the mechanism is indicated in Figure 4. The flexible guide frames is constructed along the inner wall shape [4], and the drill system was moved on the mechanism guide frame. And also the whole of guide frame is moved to the direction of tunnel axis. As the guide frame is moveable to the shape of obstacle such light, signboard and discharge fan, the concrete strength test is enforceable for all inner walls of tunnel.

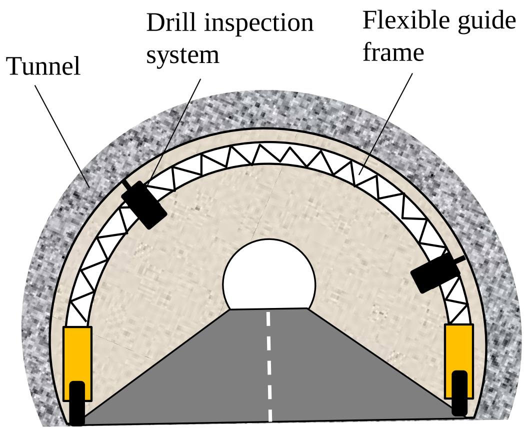

Figure 4 Application plans of tunnel inner wall inspection system using flexible guide frame with grinding drill

3 Drill Perforation Principle and Estimation Method Using Torque Control

3.1 Perforating speed and torque range

In order to be automatic the drill feed, the torque motor which could fix the rotation number was connected. This torque motor has the characteristic that can drive with the fixed number of rotation for the load in the rating torque, and even if the rotation number was decreased near 0 rapidly by influence of coarse aggregate of concrete, this motor could be drove consecutively.

Figure 5 shows the analyzed model of grinding drill. The torque value of motor is T, the rotation number is N, the feed rate is v and the drill load is F, then the following equation was obtained.

$$v = k_0 \frac{2\pi NT}{F} \qquad (1)$$

k_0 is constant value included the efficiency of motor and coefficient of rack and pinion friction.

In the control of torque motor, if the drill load of F was within the setting value of torque motor T_0, the torque value $T=k_1F$ is output corresponding to the load F. Therefore, the feed rate is indicated in Eq. (2).

$$v = 2\pi N_0 \cdot k_0 \cdot k_1 \qquad (T \leq T_0) \qquad (2)$$

In this case, the feed rate become constant value.

However, if the drill load is up to the setting value of torque motor, the feed rate v is changed according to the load F indicated in Eq.(1) because the power P ($=2\pi NT$) become a constant value P_0. In this case, the feed rate is inverse proportion to the load;

$$v = k_0 \frac{P_0}{F} \qquad (T \geq T_0) \qquad (3)$$

Here, k_0 is constant value including the motor efficiency and friction index of rack and pinion as shown in Figure 6.

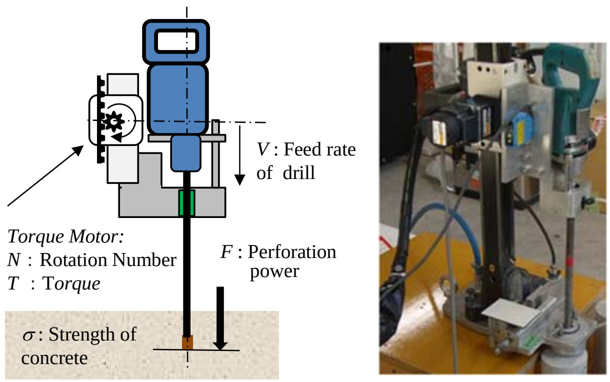

Figure 5 Picture and analyzed model of grinding drill

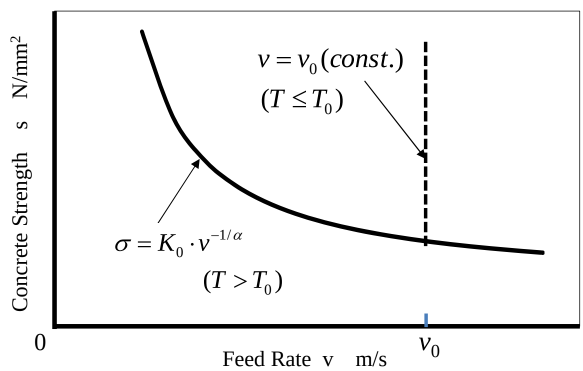

Figure 6 Concern of concrete strength and feed rate

3.2 Introduction of relation concrete strength and feed rate

If the load of drill F is proportion to the α power of the concrete strength σ, this relation is $F = k_1 \cdot \sigma^a$. This relation is substituted to Eq. (1) and is shown by σ.

$$\sigma = \left(\frac{k_0}{k_1} \frac{P_0}{v} \right)^{1/a} = K_0 \cdot v^{-1/a} \quad (4)$$

Here, K_0 is constant value. When the drill load is up to the setting value of torque motor, σ is power low curve according to *v*. In this experiment, measuring the feed rate of perforation to several strength concrete, the relation of Eq. (4) was evaluated. Using this drill system and obtaining several data of feed rate to the concrete strength in experiment, the empirical equation of the concrete strength that can simply estimate the concrete strength from feed rate can be decided.

4 Drill Perforation Principle and Estimation Method Using Torque Control

4.1 Outline of Experiment

4.1.1 Test piece

In this experiment, two type of concrete was tested. One was the ordinary concrete included coarse aggregate, the other was mortar concrete included no coarse aggregate. Adding the water to the pure concrete several times, test pieces of concrete material with different compression strength were produced. The purpose compressed strengths are about 10, 20, 40 N/mm^2. The size of test piece was assumed to be 100cm in length, 500 mm in width, and 200 mm in depth.

4.1.2 Drill parameter

First, to set the parameter of the slide block of drill, changing the torque ratio to standard torque *T*=0.1(Nm) of the motor to 10-20 %, the torque value when perforating was measured. For the each test piece, tuque condition that the perforating load *F* becomes set torque T_0 or more was selected. In this case, since the force of drill was larger than that of concrete test pieces, the feed rate of perforation is almost constant.

4.1.3 Experiment method

The perforating experiment was conducted to each test piece five times, and the device to obtain the reproducibility of the experiment was carried out. The appearance of the perforating experiment is shown in Figure 7. Each test piece was perforated up to the depth of about 150mm and its perforating time was recorded respectively. The perforating depth and torque of motor were simultaneously measured with the laser range finder installed in the slide block and these data was record in the time series in a high memory device. The interval of perforating hole was about 20mm, and it was confirmed that there was no influence on the experimental data by the next hole.

4.2 Experiment Result

4.2.1 Relation of concrete strength and perforating depth

The relation of hole depth *d* and perforating time *t* is shown in Figure 8. The depth was proportion to time and the incline to be perforating speed was found to be constant according the concrete strength. The speed was tends to decrease by concrete strength high. In spite of the experiment of the same condition, it seems to be influence of the coarse aggregate that inclines are slightly different. It was confirmed that the speed became former inclination again after the perforation of coarse aggregate was finished. So, in the experiment from which the time loss by the influence of the coarse aggregate is seen obviously, the loss time is subtracted at the entire perforating time and that each perforating speed was decided from the relation between subtracted time and the perforating depth.

The relation of concrete strength and feed rate is shown in Figure 9. When torque rate was 10% of setting torque which was over load, σ was indicated to decrease to *v*, and the correlation coefficient *r*=0.86 of the equation σ approximated by least squares method with power function being near 1, the correlation of these plots was considered to be high. Approximating these plots by power function, the curve and plots were observed to fit well.

4.2.2 Setting rate of motor torque

In the experiment of changing the torque value as shown in Figure 9, when setting T_r=10%, operating torque became 10% or more. When setting T_r=15% and20%, operating torque became 15% or less. In this case, the operating torque had an enough allowance for the perforating load. The perforating speed was constant respectively because the load was lower than the setting torque. Therefore, measuring the feed rate of perforating hole by this drill, the concrete strength was expected to

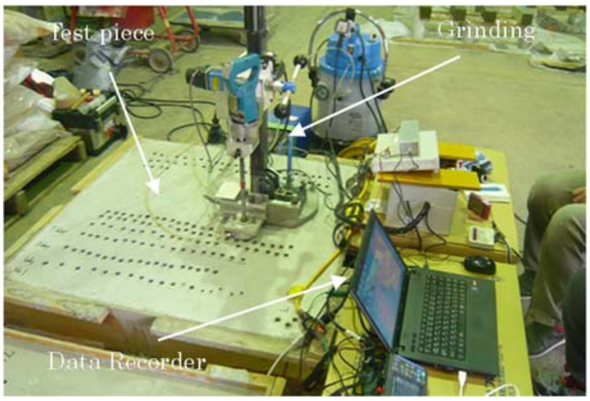

Figure 7 Appearance of the perforating experiment

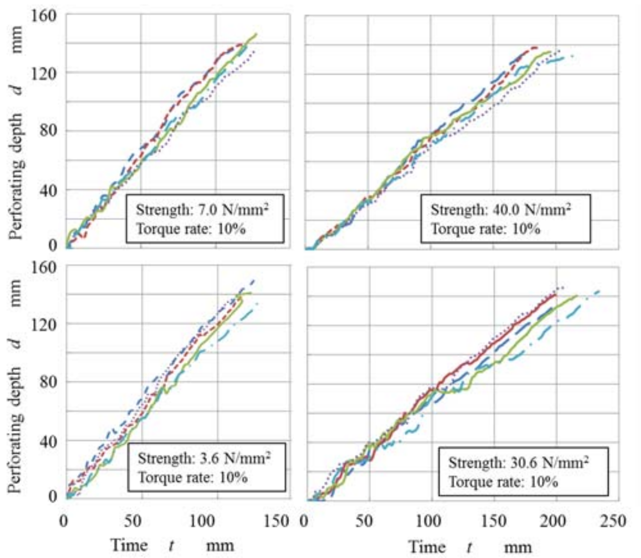

Figure 8 Comparison of perforating time and depth

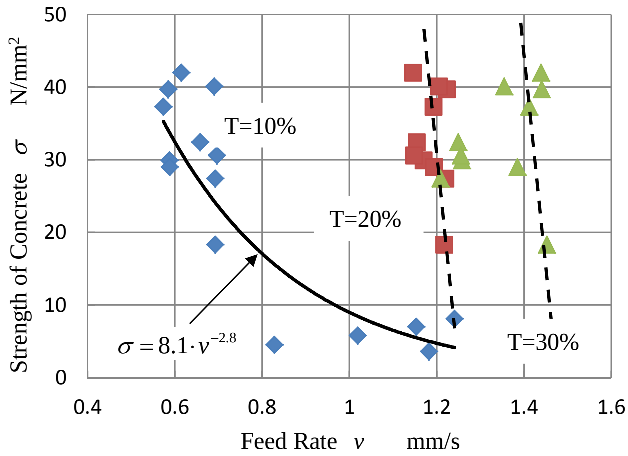

Figure 9 Comparison of concrete strength and feed rate of drill perforation

(a) Downward perforating (b) Upward perforating

Figure 10 Appearance of perforating experiment using existed concrete

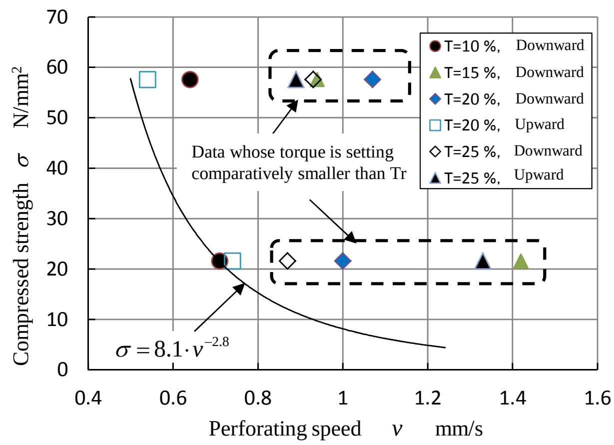

Figure 11 Relation of concrete strength and feed rate of drill perforation for the existed concrete

estimate by this method practically.
20%, operating torque became 15% or less. In this case, the operating torque had an enough allowance for the perforating load. The perforating speed was constant respectively because the load was lower than the setting torque. Therefore, measuring the feed rate of perforating hole by this drill, the concrete strength was expected to estimate by this method practically.

As the concrete strength was evaluated by above method with grinding drill, the automated work of strength estimation was developed by mobile robot as shown in Figure 2. This robot operating by wireless control, high and efficient work would be performed at several construction sites.

4.2.3 Strength estimation of existed concrete

To verify the relation between concrete strength and the perforating speed obtained by the above result, the perforating experiment and the estimation methods were applied by using the concrete existed about 1 year. In this case, the concrete strengths were 21.6N/m^2 and 57.6N/m^2. By conducting the perforating experiment in the downward and upward direction, the difference of the direction of gravitational force and the influence of the weight of the machine were examined. Figure 10-(a) shows the picture of downward direction perforating experiment and Figure 10-(b) shows the picture of upward direction one.

The relation of perforating speed and concrete strength was indicated in Figure 11. In the downward perforating result, the plot was located along the estimation curve σ, and then the curve was able to apply to the prediction of concrete strength of existed concrete. In the downward perforating result, the torque of motor setting 20% as considering the self-weight, the plot was fit to the estimation curve. In other data, the torque when perforating is data that is set comparatively smaller than setting torque T_r and it is understood to differ from the approximation curve greatly.

4.2.4 Strength estimation of mortar concrete

As for the mortar concrete, the perforating depth was observed to the relation proportional to the perforating time just like ordinary concrete as shown in Figure 7. Appling to test pieces of the several mortar concrete that the strength was different, the relation of concrete strength and feed rate of drill perforation for the mortar concrete is shown in Figure 12. In this case, the strength value σ was proportional to the right-down cave for the feed rate v. Because there is little influence of the rough aggregate with mortar, it is expected that the concrete strength was expressed to a simple linear equation. So, if we can measure the feed rate of mortar, the strength of concrete was able to estimate easily.

In these experiments, collecting the v-σ relation in advance by grinding drill system, the strength of concrete was able to estimate practically at the work site.

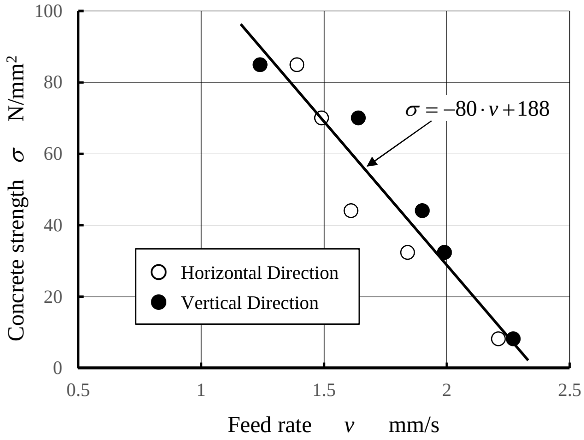

Figure 12 Relation of concrete strength and feed rate of drill perforation for the mortar concrete

5. Conclusion

In this study, the estimation method of compressed strength for the concrete construction and the autonomous mobile robot with that the small sized grinding drill were introduced. In the control using the torque motor, the feed rate of drill is expected to be a constant as the torque depending on load. However, the feed rate of drill was found to change for concrete strength and to be the approximately constant to concrete strength when the drill load was up to the setting value of torque. As a result of experiment, the comparison of the concrete strength and perforating speed was able to similar by inversed power curve. The method to estimate concrete strength from a change of the feed rate was proposed. Introducing this inspection system on a mobile robot, we would get the possibility that automated estimation of concrete strength was carried out easily at construction site. Measuring the feed rate by this drill, the concrete strength was expected to estimate practically.

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References

[1] Thomas Bock, ”Turning Points in Construction”, Proceedings of the 26th Annual International Symposium on Automation and Robotics in Construction 2009, Austin, USA, pp. 3-9, (2009).

[2] Fumihiro Inoue, Satoru Doi and Yutaka Ohta, “Development of Automated Inspection Robot and Diagnosis Method for Tile Wall Separation by Wavelet Analysis”, Proceedings of 26th International Symposium on Automation and Robotics in Construction 2009, Austin, USA, pp.379-388, (2009).

[3] Fumihiro Inoue, Eri Ohmoto, ”High Accuracy Position Marking System Applying Mobile Robot in Construction Site”, Journal of Robotics and Mechatronics, Vol. 26, No.6, pp.985-991 , (2012).

[4] Fumihiro Inoue, “A Study on Adaptive Structure Applying Variable Geometry Truss (Mechanism of Movable Arch Roof with External Panel)”, Journal of Robotics and Mechatronics, Vol. 21, No.2, pp.172-178, (2009).