Development of Mobile Inspection Robot for Concrete Wall Surface and Strength Estimation Considering Coarse Aggregate by Small Diameter Drill

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Abstract

In order to easily estimate the strength of concrete members such as piers and building walls at actual sites, we have developed a small-diameter abrasive drill and proposed a method to estimate the strength of concrete from changes in drilling speed. In drilling with a 5 mm diameter drill, the drilling speed changes due to the influence of coarse aggregate mixed in the concrete. Therefore, the drilling speed due to coarse aggregate was determined from the analysis of drilling speed, and the relationship between the average drilling speed excluding the effect of coarse aggregate and concrete strength was obtained. Next, a mobile inspection robot equipped with an abrasive drill mechanism was developed to apply this inspection method to actual sites.

Keywords

Small-diameter drill; Concrete strength estimation; Inspection robot; Roller drive; Duct fan thrust

1 Introduction

A large number of civil engineering infrastructures (bridges, tunnels, highways, etc.) constructed mainly in urban areas during the high-growth era of the 1970s have begun to reach the end of their useful lives and need large-scale repair, renewal, or reconstruction. Concrete structures, in particular, have deteriorated over time, and in some cases, their strength has been significantly reduced due to salt damage and neutralization, forcing immediate action.

In recent years, with the development of robotics and information technology, there have been reports of automatic inspections of the deteriorated condition of concrete structures using wall-moving robots and drones. The main tasks are imaging of the wall surface and simple sounding inspection [1-3]. If the reaction force of the robot is large enough, it is possible to estimate the strength of the concrete by mounting the grinding drill developed above. On the other hand, if the reaction force of the inspection drill can be kept small, it can be mounted on the current inspection system [4].

In this study, the previously developed abrasive drill was modified to estimate concrete strength by drilling a small-diameter 5 mm hole. The small diameter of the drill also reduces the reaction force due to drilling. In the experiment, strength estimation by drilling was conducted using specimens of different strength. However, when the drill bore size was smaller, the coarse aggregate inside the concrete was drilled directly, and the results were different from the original strength estimation by drilling (relationship between average drilling speed and concrete strength). Therefore, we focused on the local perforation rate of drilling and devised a strength estimation method that removes the influence of coarse aggregate as much as possible.

On the other hand, it is necessary to check the deterioration and strength of concrete structures at the actual site to ensure the integrity of the structure and efforts to repair and maintain the structure. In this study, an inspection robot equipped with a drill system for strength estimation and capable of inspecting at actual sites was developed. The inspection robot is equipped with a high-power duct fan and can easily press the drill. The robot is roller-driven, can move up and down, and is lightweight, thus gaining potential for practical use.

2 Development of Small Diameter Abrasive Drills and Drilling Tests

2.1 Outline of Experimental Equipment

Fig.1 shows an overview of the abrasive drill used in the experiment. The system consists of (1) a small-diameter drill, (2) a slide block (feeder), (3) a water circulation device, (4) a vacuum pump, and (5) an air compressor. The small-diameter abrasive drill is an abrasive drill with a diamond bit attached to its tip, which rotates at high speed to grind the mortar surface while drilling. During drilling, a water circulation device is used to cool and lubricate the bit and discharge the drilled noro water. The body of the polishing drill can be moved up and down by air pressure from an air compressor through a pressure reducing valve, which provides a (constant) pressing force for the drill during drilling. The tip of the drill consists of a diamond bit, and the drilling method is to drill while polishing the concrete. Experiments using an abrasive bit with a relatively large bit diameter have shown that the drilling depth is almost proportional to the drilling time, and the drilling speed is almost constant under the same conditions such as drill pushing force and rotation speed. In the experiments, five kinds of concrete specimens of different strength were prepared in order to understand the performance of the developed drilling system.

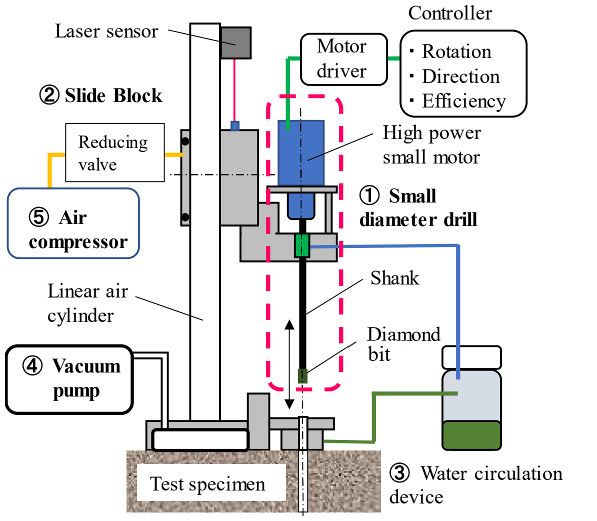

Fig.1 Overview of the drilling device and measurement system used in the concrete

2.2 Changes in Drilling Gradient and Internal Observation of Drilling

When drilling with a small-diameter (5 mm) drill, the drilling speed is not always constant because the drill may directly drill through the coarse aggregate scattered inside the concrete. Figure 3 shows the relationship of drilling depth to drilling time when drilling a concrete specimen. In addition, images of the perforation taken continuously by an endoscope are also shown.

Observation of the state of the drilling depth shows that the area near the starting point of drilling (above: Fig.2) is white due to the finishing layer of concrete. From the start of drilling to around 60 seconds, the change is relatively linear, and the layer is a mixture of white (Fig.2) and black (coarse aggregate) (below: Photo 2). Around Fig.2, the proportion of mortar increases and the gradient of perforation is slightly higher.

In the range of 130 to 190 seconds of drilling time, the drilling depth is almost constant and the black coarse aggregate is drilled (Fig.2 (4)). It takes a considerable amount of time to drill through the coarse aggregate. After passing through the coarse aggregate, a layer of coarse aggregate and mortar is formed again, and the perforation gradient increases (Fig.2 ⑤) and then reaches the longest part of the perforation (Fig.2 ⑥). Thus, it can be seen that the 5 mm hole drilled through a mixed layer of coarse aggregate and mortar, and that the drilling gradient (drilling speed) changes constantly.

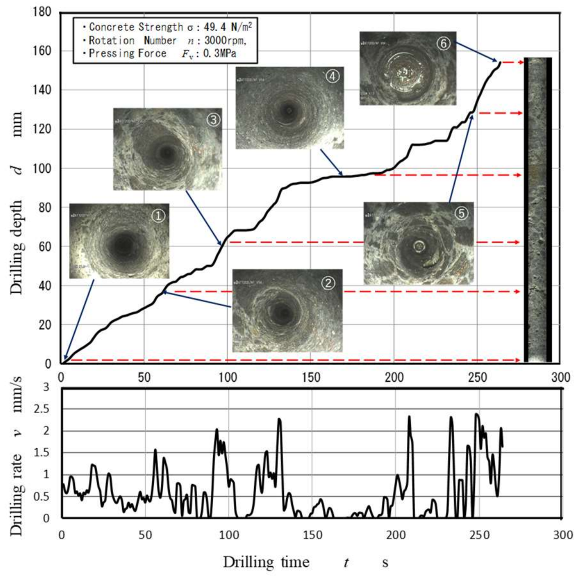

Fig.2 Relationship of depth and drilling speed to time for concrete specimens containing coarse aggregate

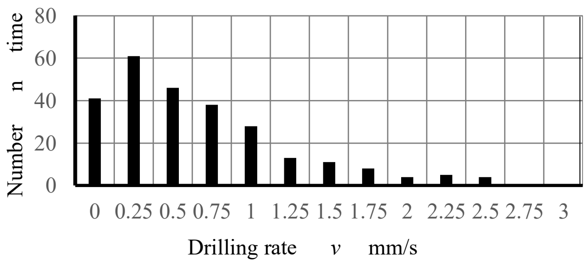

Fig.3 Time distribution for each drilling speed range

2.3 Coarse Aggregate Condition and Change Distribution of Drilling Speed

Since the drilling gradient varies with the internal condition of the concrete, the drilling speed per second (mm/s) was calculated. Figure-3 (bottom) shows the relationship of drilling speed for each drilling time. It can be clearly seen that the drilling speed changes in response to the gradient of the drilling depth. It can be seen that the drilling speed is smaller than 1.0 mm/s in the area affected by the coarse aggregate. Figure 4 shows the distribution of the number of hours for each range of drilling speed. It can be seen that the number of hours is concentrated in the range where the drilling speed is smaller than 1.0 mm/s. This area is affected by the coarse aggregate. From this result, the average drilling speed $v_{mean,i}$ excluding the effect of coarse aggregate is obtained by excluding the area of small drilling speed and dividing the remaining total number of hours by the total drilling depth (the drilling depth is subtracted because drilling progresses according to the number of hours even if the drilling speed is small), using the Eq. (1). where L_{Total} is the total drilling depth (155 mm in this experiment), T_{Total} is the total drilling time, i is the number of the speed range in which the effect of the stone layer is removed, $v_{\_(c,i)}$ is the lower limit of the i_{-th} speed range, and $t_{\_i}$ is the number of hours for the i_{-th} speed range.

$$v_{mean,i} = \frac{L_{Total} - \sum_{k=1}^{i}\{(v_{c,k} + 0.125) \times t_k\}}{T_{Total} - \sum_{k=1}^{i} t_k} \tag{1}$$

2.4 Strength Estimation Considering Effect of Coarse Aggregate

Drilling tests were conducted on five types of concrete specimens with high coarse aggregate content. Figure-6 shows the relationship between average drilling speed and compressive strength. In the range where the drilling speed v is small ($v_{\_(c,i)}$ ~ 0.5), the plots are scattered in different places, and it is difficult to see a relationship between the average drilling speed and the specimen strength. However, for $v_{\_(c,i)}$ = 0.75 to 1.0, each blot is aggregated and the average drilling speed and specimen strength line up linearly (red dashed lines in the figure). Using this relationship, it may be possible to estimate the concrete strength from the average speed of drilling. On the other hand, for $v_{\_(c,i)}$ = 1.25, the values of the plots are again scattered and the relationship becomes less relevant. This may be due to the fact that even the drilling speed for normal drilling (when there is no influence of coarse aggregate) is excluded.

Thus, when drilling with a 5mm abrasive drill, if v_c = 0.75, the concrete strength σ can be estimated from the slope of the straight line obtained in Fig 6 using Eq. (2).

$$\sigma = 83.9 - 59.3 * (v_{mean,i} - 1.5) \tag{2}$$

However, Equation (2) is a relational equation for the specimens used in this study, and may not necessarily be applicable to specimens with different coarse aggregate and other materials. By introducing the relationship of average drilling speed without the effect of coarse aggregate, it was found that concrete strength can be adequately estimated even in drilling tests using small-diameter drills. The results of this study are as follows.

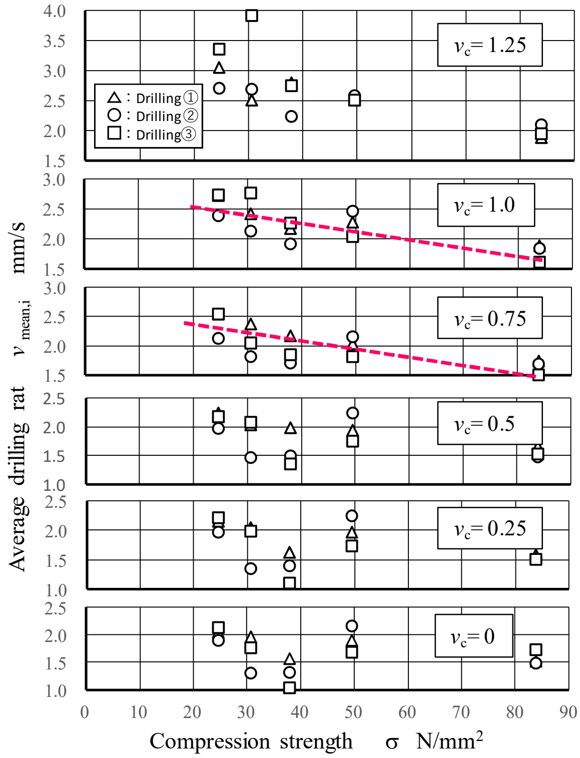

Fig.4 Relationship between average drilling rate and compressive strength considering range of drilling rates

2.5 Outline of Inspection Robot

An inspection robot equipped with a drill system for strength estimation was developed for on-site inspection. As shown in Fig. 5, the inspection robot is equipped with an automatic vertical moving mechanism and various sensors to enable various inspections of vertical wall surfaces.

2.5.1 Vertical Moving Mechanism

When robots are used for inspection and repair of wall surfaces, the types of devices used for vertical movement are generally of the drone flying type or the rope winding type with the device suspended from above. However, conventional methods have disadvantages such as being affected by wind, difficulty in approaching walls, and limited lifting weight of the inspection device. In this study, the tether and roller drive principle were used for vertical movement, which is a simple mechanism, has good positional accuracy, and has excellent stopping performance. During inspection, the device can be fixed to the wall surface via casters, and lanes to be inspected are set up and inspected in sequence.

The climber can be raised and lowered under autonomous control, and by turning on the start switch, it can stop at each section according to a pre-set program. The system can be switched between wired and remote control, and can be checked visually or with a live camera mounted on the inspection equipment. After completing the inspection to the top under autonomous control, it can be lowered by sensor detection. The power supply is powered by a battery, but for longer inspections, a wired connection is used to supply power. Safety ropes and mechanical brakes are installed to prevent falling.

2.5.2 Horizontal Push against Wall

Multiple casters are mounted on the wall side of the inspection system to push to maintain the verticality of the small-diameter drill and the wall surface. A high-power duct fan is located in the same line across the drill to press the main unit and the drill against the wall. As shown in Fig.6, when measuring the strength of the wall surface, the small-diameter drill can be moved via a slider, enabling drilling with a constant force of pressing. The maximum force to press the entire inspection system by two duct fans against the wall surface is about 30 N, which is sufficient for the pressing force (15 N) for the strength estimation experiment described in Chapter 2.

2.6 Operation of the Small Diameter Drill for Wall Surface Inspection

The drill is moved to a predetermined height using a climber and pressed against the wall surface using a ducted fan. After setting it in the position to be inspected, the small-diameter drill for wall surface inspection is operated. The drilling procedure is as follows (1) to (3).
(1) The compressor is used to bring the tip of the drill into contact with the wall surface.
(2) A water circulation system is activated to eliminate concrete dust generated during drilling.
(3) Operate the motor connected to the drill to drill.

After 5~10 cm of drilling is completed, the motor is stopped and the drill body is pulled up by a compressor. This series of operations is performed by remote control. The mobile inspection robot and strength estimation system have already been completed and will be tested at actual sites for practical use.

3 Conclusion

In order to simply estimate the strength of concrete members for vertical walls such as bridge piers and buildings at actual sites, we developed a small-diameter abrasive drill and proposed a method to estimate the strength of concrete from the change in its drilling speed. In drilling with a 5 mm-diameter drill, the drilling speed changes due to the influence of coarse aggregate mixed in the concrete. Therefore, the drilling speed due to coarse aggregate was found from the analysis of the drilling speed, and the relationship between the average drilling speed excluding the effect of coarse aggregate and concrete strength was found.

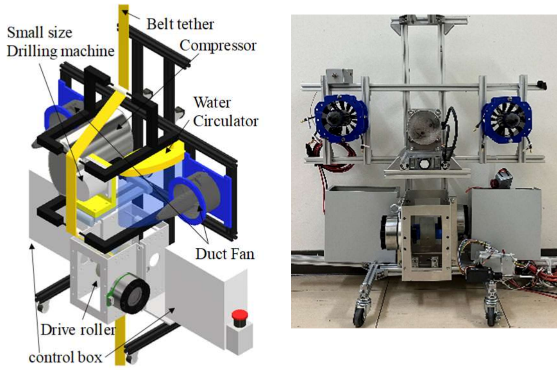

Fig.5 Overview of the inspection robot equipped with the drill system for strength estimation

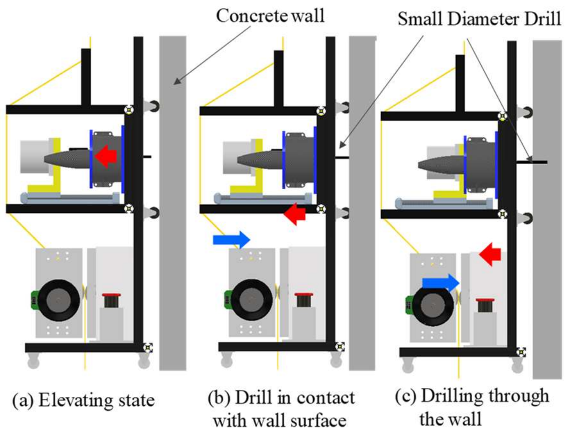

Fig.6 Operation of a small-diameter drill for wall surface inspection mounted on an inspection robot

Next, a mobile inspection robot equipped with a drill mechanism was developed to simplify this inspection method. In the future, we would like to use these in actual sites to add the necessary systems and the possibility of calibrating them for each site.

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