Ferroconcrete Dismantling Technique using Induction Heating

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Abstract

To increase the quality of recycling, a new demolition technique is required that can work in parallel with existing crushing methods, which use large equipment with high crushing efficiency. Moreover, the efficient collection of the remains from the fractional dismantling method needs to be considered based on its procedure, and the technology for partial dismantling that is efficient in remodelling, maintenance, and reinforcement has to be developed. In this study, the temperature-increasing characteristics of rebars inside ferroconcrete with respect to their arrangement was investigated by partial rapid heating through high-frequency induction heating. Based on this, the chemical and physical vulnerability characteristics of ferroconcrete due to the thermal conduction generated on the rebar surface and the cracks caused by the thermal expansion pressure of the rebar were verified. In addition, the objective of this study was to verify the applicability of the technology by specifying the vulnerability range of ferroconcrete based on the heating range with adequate consumption of energy.

Keywords: Recycling; Ferroconcrete; Heat Induction; Ease to Scrap; Weakening

INTRODUCTION

Recently, the use of fractional dismantling construction for remodelling, maintenance, and reinforcement works has increased rapidly. Therefore, the development and application of new techniques for damage prevention and safety enhancement of existing structures is essential [1,2]. By promoting development in the current dismantling industry, the safety of dismantling construction, reduction in environmental pollution, proper processing of generated wastes, and improvement of recycling rate could be achieved [3].

This study aims to develop a technique for fractionally dismantling ferroconcrete structures using high-frequency induction heating technique and a selective heating using rebars inside ferroconcrete as a conductive resistant. This method could decrease the noise and pollution associated with ferroconcrete dismantling, and the energy usage could be reduced by increasing the rebar collection rate inside the separated ferroconcrete members of the framework. Moreover, the recycle process could be minimised, and the recycling rate of construction wastes could be improved.

TECHNICAL OVERVIEW

Heating mechanism of internal rebar by high-frequency induction heating (Joule heating)

The high-frequency heating methods include high-frequency induction heating and high-frequency dielectric heating. The dielectric heating enables uniform internal heating and although it can heat selectively the space under an electric field, permittivity might vary significantly during the heating. Because it requires high frequency power compared to induction heating, it requires a power conversion device such as an inverter. The induction heating is a method of heating an object such as metals by using the electrical energy transformed from the high frequency current transport conductor, which is the induction coil.

When an alternating current flows in the coil, a magnetic force of varying strength is generated along the line of the coil, as shown in Figures 1 and 2. If a metal conductor is placed near this magnetic field, Eddy currents are induced inside the metal. and because the metal has an electrical resistance, Joule heat is generated of power equal to the square of the current. As only the metal is heated by this phenomenon, there is no danger of temperature increase in other areas [4,5].



Magnetic flux $\boldsymbol{\Phi}$ depending on alternating current i_1



Induced current (Eddy Current *i*₂) **Figure 1:** Mechanism of high-frequency induction heating [8]

Eddy current (Induced current)



Figure 2: Thermal model of steel reinforcement based on high-frequency induction heating [8]

Heating model of rebar using high-frequency induction heating

As previously mentioned, if an alternating current flows in the induction coil, an Eddy current is generated, and the metal is heated. In this case, the Eddy current acts as a heat source whose strength depends on the electrical resistance of the metal.

In the case of magnetic substance, the efficiency of the heating surface gets higher because the depth of penetration becomes shallow depending on the increase of relative permeability. In case of using steel reinforcement with relatively higher permeability, localized heating on the surface of steel reinforcement is possible because induced current is concentrated on the areas facing the heating coil when the magnetic field occurred from the coil is absorbed into the surface of the metal. Selective partial heating can be achieved in the induction heating method because the range of the magnetic field can be adjusted by changing the diameter of the induction coil [6, 7, 8].

VULNERABILITY CHARACTERISTIC OF FERROCONCRETE USING HIGH-FREQUENCY INDUCTION HEATING

Overview of experiment

In this study, the vulnerability characteristics of ferroconcrete are examined using a high-frequency induction heating method. As shown in Table 1 below, the experiments were performed using 3 W/C compositions, 4 varying lengths of rebar, and 4 heating distances at two different conditions of air dry condition and absolute dry condition. For each combination of experimental conditions, 3 test specimens were made, and all of the experiments were performed based on a ferroconcrete that is 28 days old.

Vulnerability mechanism of ferroconcrete using highfrequency induction heating

The high-frequency induction heating method is based on the principle that the concrete around the rebar becomes vulnerable as the heat generated from the rebar surface is transmitted to the concrete. In this method, heating occurs inside the concrete without direct contact with the heated object, i.e. the internal rebar. As shown in Figure 3, it is possible to rapidly heat the internal rebar inside the ferroconcrete because the energy density is much higher in this method compared with ohmic heating and microwave heating methods based on combustion.



Figure 3: Vulnerability model of ferroconcrete based on highfrequency induction heating

In concrete, the calcium silicate hydrate (C-S-H) gel accounts for 60–70% of the cement hydrate, and Ca(OH)₂ accounts for 20–30%. Normally, the free water in the capillary tube pores evaporates at about 100°C, and the gel collapses as the first phase of dehydration at 180°C. Ca(OH)₂ decomposes at 450-550°C, and C-S-H decomposes at over 700°C. Since the concrete matrix is a multi-pore structure composing the cement hydrate and absorbed water and composed of capillary tube water, gel water and free water and composes, concrete dehydrates in a high temperature environment, resulting in pore structure changes and chemical changes. These in turn influence the physical characteristics of the concrete, which depend on the types of cement, mixture, and aggregate used. The compressed strength of concrete tends to significantly decrease above 500°C although it shows no substantial changes up to 200°C [9, 10].

The heat conductivity of concrete varies according to mixture rate, density, nature of the aggregates, moisture state and type of cement. In general, it was known that the heat conductivity of concrete is 2.5–3.0 kcal/mh°C, and the heat conductivity at high temperature it tends to decrease as the temperature increases. Harmathy reported that moisture increased the heat conductivity of concrete in below 100°C [11], but Schneider reported that usually heat conductivity gradually decreased in all ranges of temperature as the internal temperature of concrete increased [9].

In addition, the model equation for heat conductivity rate according to the ENV 1994-1-2 standard and the European Convention for Constructional Steelwork (ECCS) is given by Equation 1 [10].

$$K_{\rm c} = 2.0 - 0.24 \left(\frac{T}{120}\right) + 0.012 \left(\frac{T}{120}\right)^2$$
(1)
× 0.86 kcal°C/hm

where

 $K_{\rm c}$ = heat conductivity rate

T = temperature

In this study, a rebar commonly used in ferroconcrete is used as the electrically conductive object for high-frequency induction heating. A crack is induced on the external surface of the concrete confining the rebar by the rebar expansion pressure caused by the high-frequency induction heating. Moreover, the degradability of the ferroconcrete due to chemical vulnerabilities inside the concrete is utilized in the dismantling mechanism by conducting the high heat of the rebar surface to the concrete that surrounds the rebar.

Experimental conditions and levels

In this experiment, the high-frequency induction heating using a rebar as the electrically conductive object was investigated by constructing a ferroconcrete test object. The temperature characteristics and vulnerability of concrete with respect to the heat conductivity were evaluated during the experiment.

The distance from the induction coil to the rebar was considered as the sheath thickness, and ferroconcrete specimens of different sheath thicknesses were produced. The experiments were then carried out to obtain the adequate output suitable to each sheath thickness by changing the parameters of the high-frequency induction heating device. A standard specimen was prepared for each condition,



Figure 4: Impedance matching of high-frequency induction heating

and a relative evaluation was performed with respect to the residual strength and vulnerability of the concrete. The experimental levels, properties of the materials used, and compositions of the concrete mixtures are shown in Table 1–3, and the power watt (w) of the high-frequency induction heating device is shown in Figure 4.

Mark	Output (kW)		Rebar length (mm)		W/C (%)			Heating distance (mm)			
D10	5	10	170	430	0.40	0.50	0.60	20	30	40	50
D19											
D25											
D32											

Table 1: Experimental conditions and levels

Table 2. Properties of materials used in experiment

Component	Material	Properties
Cement	Common Portland cement	Density: 3.16 g/cm ³ , Specific surface area: 3330 cm ² /g
Fine aggregate	Natural sand	Surface dry density: 2.60 g/cm ³ , Fineness modulus: 2.55
Coarse aggregate	Crushed stone 5-20 mm	Surface dry density: 2.66 g/cm ³
Chemical admixture	AE water reducing admixture	Polycarbonate acid

Slump	Air	W/C (%)	G _{max}	S/a	Wunit		Weight mixture	Admixture	
(mm)	(%)		(mm)	(%)	(kg/m^3)	С	S	G	
134	2	0.40	25	42	180	450	707.2	999.1	C (0.3%)
131	1.9	0.50	25	45	180	360	799.1	1003.44	
134	1.6	0.60	25	47	180	300	849.36	979.92	

Table 3: Compositions of concrete mixtures used in experiment

* Wunit: Unit quantity of water, C: Cement, S: Sand, G: Aggregate

Production of specimen and method of experiment

In this experiment, one deformed rebar specimen of 180mm length laid in $100 \times 100 \times 150$ mm concrete (W/C=50%) was built and it was heated by the high frequency induction heating device. The surface and internal temperature of ferroconcrete were measured by a thermocouple and the reduction in bonding strength was measured by a rebar drawing experiment. There are five combinations of thickness and sheath of rebar: D10-30mm, D19-20mm, D19-30mm, D19-40mm, D25-30mm.

The rebar drawing experiment was performed by producing three specimens with the same conditions for each combination. The rebars of D10, D19, D25, and D32 were cut in lengths of 430 mm, and the beam-shaped ferroconcrete specimens were then produced by setting the sheath thickness to 30, 40, and 50 mm. The production details for each specimen are shown in Figure 5. Temperature increase

characteristic and temperature distribution characteristic were investigated according to the water-bonding material ratio, sheath thickness, rebar type, as well as the change in frequency used.

In the experiment using the D19 rebar, two more conditions were included, namely the "air dry" condition and the "absolute dry" condition. For each of the conditions, the residual bond strength before and after the heating of the rebar and the crack formation in the concrete from its heat conductivity were measured. To further confirm the residual bond strength and the crack formation characteristics of the test specimens, cross-comparisons were made with additional test samples which were sequentially heated along its length using a heating method different from what is included in this. As for the D10 rebar, samples were collected before and after they were heated to determine the chemical changes in the materials by examining the change in the pore structures.



Figure 5: Specimen production and experimental methods

EXPERIMENTAL RESULTS AND ANALYSIS

Temperature increase of single ferroconcrete due to high-frequency induction heating

Compression strength with respect to concrete composition:



Figure 6: Stress distortion curve of normal concrete (28 days)

Test specimens were produced for different concrete compositions because it was hypothesised that the temperature increase and vulnerability characteristics would vary according to the water-cement ratio. The compression strength test for the material aged of 28days was conducted as shown in Figure. 6 per each specimen and since then, an evaluation with respect to the vulnerability characteristics was performed with high frequency induction heating. The compression strength specimens were cured under the air dry condition in order to account for the climatic conditions of the site.

Temperature increase due to high-frequency induction heating:

Figure 7 showed the result of experiment for temperature increase characteristics of concrete surrounding rebar using thermocouple. As shown in Figure 5, Type 1, the temperatures were measured at 2 points near the center of the rebar test specimen, and also at the 2 points located 15 mm away from the bottom (hereafter referred to as the "side") edge of the experimental apparatus. The test sample was heated for 360 s at 6 kW power. At each of the measuring points, a thermocouple was inserted at depths of 10 mm and 20 mm to measure temperatures. The results of the experiment showed that except for the D19-30 mm specimen, the temperature decreased in an order of 10 mm depth at rebar center, 20 mm depth at rebar center, 10 mm depth at rebar side, and 20 mm

depth at rebar side. The measured temperatures at 10 mm and 20 mm from the centre of the rebar were in the range $46-90^{\circ}$ C.

As shown in Figure 7(d) for the D19 rebar, when the distance from the induction coil was 40 mm, the temperature difference between the 10 mm and 20 mm depths from the centre of the rebar was not significant. In conclusion to the overall results, there was a temperature difference of 74–83°C at the side measurement point. However, it is judged that there is no significant influence of the concrete composition on the heat conductivity as the difference between the maximum and minimum temperatures is within 30°C. All results were evaluated results of the heated 360 seconds.

The maximum temperature at the centre of the D10 rebar after heating for 360 s at a distance of 30 mm was 510° C.

Using inductive heating, it is possible to rapidly heat up the surface of the rebar. As a result, the concrete surrounding the rebar is weakened due to heat conductivity. It is believed that this enables the system of weakening the concrete, by inducing the cracks. However, depending on the heat conductive properties of the concrete, it takes considerable amount of time for the surface of the concrete to reach a high temperature. Due to this, it can be concluded that the safety of the workers can be ensured, from any injuries such as burns.

As shown in Figure 7(a), when the corresponding rebar laid in concrete was heated, the maximum temperature of the concrete 10 mm from the centre of the rebar surface was 106°C. In the cases of D19 and D25, the maximum temperatures after heating only the rebars were 651°C and 613°C, respectively, as shown in Figure 7(c), (e) and 7(f), whereas when heating the rebars laid in concrete, the maximum temperatures of the concrete 10 mm from the centre of the rebar surface were 171°C and 139°C, respectively. The differences between the two conditions may be due to the influence of the heat conduction time from the rebar surface to the outside of the concrete. Moreover, the heat conductivity varies depending on the internal matrix of the concrete, and the heat is transmitted rapidly according to the rapid heating characteristics of the internal rebar.



(a) D10 – 30 mm



(b) D19 - 20 mm



Figure 7: Temperature increase of ferroconcrete due to induction heating (type 1) & Reinforced heating results

However, since it takes a time to transfer the heat that was occurred inside the rebar to the surface, which was caused by evaporation of the internal free water, the heat produced on the surface of the rebar is high at the concrete that surrounds the rebar while the heat at the surface of concrete is lower.

In this experiment, the 450mm ferroconcrete member using rebar was tested in two states, air dry condition and absolute dry condition. The four types of rebar, D10, D19, D25, and D32, were used, and the sheath thickness was varied as 30, 40, and 50 mm, as shown in Figure 5 (Type 2). As shown in Figure 8, the temperature at a point 10 mm from the internal rebar surface was measured. For the specimen with 30 mm sheath thickness, the maximum temperature difference between the air dry and absolute dry conditions was more than 45°C. D19 and D25 specimens with high heating efficiency showed the highest temperature under the absolute dry condition.

A clear temperature difference was also observed between the two specimens with high heating efficiency in the case of 40 mm sheath thickness. However, there was no significant difference between the D10 and D25 specimens, which have low heating efficiency. In the case of 50 mm sheath thickness, the temperature difference was not large.

As an overall result, the slope of temperature increase curve in the absolute dry condition showed relatively consistent increasing curve comparing to a slope of temperature increase curve in the air dry condition. It is supposed that the irregular temperature increase in the air dry condition was because the gel water (water included in the gel) evaporated at over 80°C.

With the penetration characteristics of the high frequency induction heating, the heating efficiency is rapidly dropped at over 50mm of sheath thickness and the gap in temperature increase was reduced at 5kW. At10Kw output, the experiment result of a specimen using D25 rebar showed similar result in temperature increase compared to that of a specimen using D10 with 30mm concrete cover.

However, it was increased only up to 60°C and did not show significant difference from the increase gap of 5kW. This may be attributed to the decrease in heat efficiency due to the decrease in the rebar section within the magnetic field.











Figure 8: Temperature increase of ferroconcrete due to induction heating (type 2) (C: center, C9: 90 mm distance from the center point)

Change in physical and mechanical characteristics due to high-frequency induction heating

Cracking of ferroconcrete :

The 400mm-length specimens were built using rebars of D10, D19, D25, D32 and sheath thickness varied at 30mm, 40mm, 50mm. As shown in Figure 9, the heating coils were placed at the center of the specimen with 400mm in length and 5kW in power, and the status of crack was measured after heating for 360 seconds. In the 30 mm and 40 mm sheath thickness specimens, cracks occurred on the surface of the specimen within 30 s of heating. Moreover, in the case of 50 mm sheath thickness (concrete cover), cracks appeared within a minute, except in the D10 specimen, in which no cracks occurred.

In the case of 30 mm sheath thickness, cracks occurred in all the specimens in both the rebar and vertical directions and at both ends of the concrete around the induction coil. For the 40 mm sheath thickness, cracks appeared at both ends in all the test specimens except D10. In both the 30 mm and 40 mm specimens, cracks appeared at both ends because of the high heat efficiency at these sheath thicknesses. In the case of 50 mm sheath thickness, a single crack from the rebar to the surface of concrete occurred within a minute of heating in all the test specimens except D10. The D10 rebar was different from the other rebars because its cross-sectional area was small, and it is thought that the crack generation progress was different in the D10 specimens because the heat expansion force was small.

As shown in Figures 10 and 11, the front face of the specimen using D19 rebar with 400mm in length was sequentially heated in horizontal direction for 360 seconds. As a result, a crack was occurred along the vertical direction of rebar and a crack along with horizontal direction. Moreover, the result of progressive cracking could be observed along the side of the rebar where it was exposed. In the case of continuous heating, it is inferred that the bonding strength of the rebar strongly influences the decrease in the restraint stress and the detachment of the rebar and the concrete.



Figure 9: Measurement result in crack occurrence depending on induction heating







(a) Under induction heating







ting(b) Centre heating(c) Entire surface heating(d) Crack around rebarFigure 11: Measurement photos of crack occurrence due to induction heating

Change in pore structure

A material in cement system is a multi-pore stucture that contains a hydrate, absorbed water, capillary water that exists in thr pores that consist of a hydrate, a gel water and a free water. In a high-temperature environment, the structure and chemistry of the pores change because of dehydration and the dehydrated water. This can be assessed by the pore distribution and structural characteristics.

For each concrete composition, the ferroconcrete specimen was heated by induction heating for 360 s, and a concrete sample was collected 1 mm from the rebar surface. As shown in Figure 12, the pore structure change showed an overall peak at approximately 0.1 μ m. The entire volume of the void increased as the temperature of the concrete increased, and the peak in the pore diameter distribution moved toward larger values. The volume of the void generally increased as a result of the heating, and this tendency was the same regardless of the water–cement ratio. The increase in the volume of the void showed slight differences depending on the type of specimen and mixture condition, but the cumulative volume of the void gradually increased as the heating temperature increased.

In the case of 40% water–cement ratio, pores of diameter 0.05 μ m or less decreased, and pores of diameter 0.1 μ m or more rapidly increased as a result of the induction heating. Moreover, the cumulative volume of the void gradually increased. In the case of 50% and 60% water–cement ratios, pores of diameter 0.05 μ m or less and pores of diameter 0.1 μ m or more significantly increased.

In general, a hydrate that comprise concrete composes different volume ratios based on the hydration state of cement or a water-bonding ratio, and in the case of small waterbonding ratio, both capillary water and porosity are small, and the number of capillary tube increases.

In the case of hardening cement, about 60-70% of the solid matter is a hydrate of the C-S-H system and about 20-30% is calcium hydroxide. Certain volume ratio, the amount of capillary water is different for different water-cement ratios, but if the gel water evaporates, the increase in the porosity is almost the same because the volume ratio is maintained. The increase in porosity results from water evaporation, dehydration and variation of the hydrate, and temperature changes. Consequently, The hardening body of cement becomes porous because of the increase of porosity, and since the increase of porosity influences the properties of concrete, it also influences the decrease of compression strength and the vulnerability. In particular, this is clearly shown in the 5 µm sample's D10-40% hydrate. The calcium hydroxide seems to have changed due to its greater amount existing in the sample, compared to the other specimens. The increase in porosity due to induction heating occurs as a result of minute fractures in the concrete and dehydration of the gel water and capillary water. Moreover, the chemically bonded hydrate of the S-C-H system and calcium hydroxide decomposes, and the bond water evaporates.

Residual bonding strength of rebar

The ferroconcrete structure efficiently combines and integrates two heterogeneous materials, namely the rebar and the concrete. Thus, the coherence of these two materials significantly influences the performance of a member of the framework. The coherence of the rebar and concrete mainly depends on three factors: 1) chemical adhesion between two materials 2) friction 3) internal mechanical reaction among rebar, concrete that surrounds rebar, and rebar rib. At lowstress conditions, the tensile stress of the rebar, as shown in Figure 13(a), is transferred to the concrete, and this force acts as a slope compression force on the concrete. Moreover, as shown in Figure 13(b), the radial compressive force maintains a balance with the tensile stress that is generated at the concrete around the rebar, and the magnitude of the force that is transferred from the rebar to the surrounding concrete is determined by occurrence of cracks in the concrete sheath and the destruction of the tension ring that comprises the tensile force [12].



Figure 12: Pore structure change of single ferroconcrete due to induction heating



Force transfer of ferroconcrete

A residual adhesive strength test according to ASTM C 234 that targets the deformed bar was conducted [13]. For the D19 rebar, a specimen that was not heated was compared with a specimen that was subjected to induction heating at the centre only and another specimen whose entire surface was subjected to induction heating in the rebar direction. Then, a calculation was performed in order to evaluate the restraint stress quantitatively with respect to the change in sheath thickness. As shown in Figure 14, the compressed force *C*, given by Equation 2, acts on the rebar with diameter *d* and bond length *l* and is transferred to the concrete by the compressed stress of the rebar. The unit mean bond stress $\tau_{\rm b}$ acts on the surface area πdl of the rebar.

$$C = \pi d l \tau_{\rm b} \tag{2}$$

where

- C = compressed force acting on rebar
- d = diameter of rebar
- l = length of specimen
- $\tau_{\rm b}$ = unit mean bond stress



Compression force of radial form

Figure 13: Force transfer structure of rebar



Figure 14: Force transfer structure of rebar applied to experiment

The chemical friction was disregarded in this experiment. As shown in Figures 15 and 16, crack occurred due to the rebar rib with the widest area according to the heat expansion pressure generated by the induction heating. Therefore, it is inferred that the bond stresses of the rebar rib and concrete, and hence the bonding force, are reduced. Moreover when comparing the non-heated specimen with the specimen that was heated at the centre only, it was assumed that the same load was applied on the bottom area of the rebar rib. As a result, compared with the non-heated specimen, the specimen that was heated in the centre only showed 58%, 8.3%, and 11.5% reduction in the stress at the bottom of the rebar rib and

58%, 8.9%, and 12% reduction in the concrete stress for the sheath thickness of 30 mm, 40 mm, and 50 mm, respectively. Furthermore, the specimen whose entire surface was heated along with rebar direction showed 61%, 29%, and 11.5% reduction in the stress at the bottom of the rebar rib and 63%, 27.8%, and 12% reduction in the concrete stress for the sheath thicknesses of 30 mm, 40 mm, 50 mm, respectively.

In the case of 30 mm sheath thickness, which has high heating efficiency, more than 60% reduction in bonding strength was observed. In the case of high heating efficiency, the overall temperature of rebar was increased according to thermal conductivity and it was confirmed that there was no significant difference with the specimen whose entire surface was heated. However, at low heating efficiency, there was more than a 20% difference between the partial heating and entire surface heating cases. It is thought that the range of rebar expansion pressure according to thermal conductivity is reduced because the heating efficiency is reduced according to the distance. In the case that a crack that occurred at the rebar rib extended to the concrete surface, it was confirmed that the reduction in concrete the stress was in direct proportion to the stress reduction for which the rib was responsible.

In the specimens using the D25 rebar, the bonding strength was reduced by 27.3%, 23.2%, and 17.4% at the sheath thicknesses of 30 mm, 40 mm and 50 mm, respectively. Even though the stress in the rib and the residual adhesive strength of the concrete were reduced proportionally, it was confirmed

that the reduction in the residual adhesive strength of the rib was slightly higher. In the case of the D32specimen, its adhesive strength decreased by 15.4%, 17%, 17% in the order of 30mm, 40mm and 50mm, respectively. If the cross section area of attachment is wide and the heating efficiency is reduced, the reduction rate of adhesive strength was also decreased according to induction heating.

There were no significant differences between the reduction in the stress of the rib and the reduction in the residual adhesive strength of the concrete. In the specimens using the D10 rebar, the results were slightly different because of the changes in stress distribution due to the influence of rebar buckling in the experiment. In addition, there were no significant differences in the reduction of the bonding strength. In the case of partial induction heating, the thermal conductivity ratio is decreased as the diameter of rebar increases and it was confirmed that the size and range of the heat expansion force of rebar rib were decreased together as the heat loss of heat transfer coefficient was increased in proportion to the area.

If cracks occur because of the expansion force of the rebar, it is thought that most of cracks generated at the rebar rib are transferred to the surface of the concrete, and thus the stress and the bonding strength decrease. Moreover, the heat generated at the surface of the rebar rib makes the concrete at the bottom of the rebar rib and the concrete between the rib and rebar vulnerable.



Figure 15: Experimental result of attachment strength of ferroconcrete depending on induction heating (D00 - 000 : D rebar diameter - heat distance mm - heating - all heating)



Figure 16: Experimental result of attachment strength of ferroconcrete depending

CONCLUSION

From the results of the experimental analysis conducted in this study, the following conclusions were drawn:

(1) In the case of single bar concrete, when the rebar inside concrete is indirectly heated using high-frequency induction heating, local, selective heating is possible because the temperature difference between the concrete within the heating range and the concrete outside heating range is significant.

(2) In the case of induction heating with 5 kW maximum output, a rapid decrease in the heating efficiency occurred within the heating distance of 50 mm, whereas at the output of 10 kW, excellent heating efficiency was observed at 50 mm.

(3) As a result of the induction heating, cracks occurred in the vertical direction, and for a short heating distance, cracks occurred at both ends. In addition, if the cross-sectional area of the rebar decreased, the range of the cracks increased because of the increase in the heat conductivity efficiency, but decreased because of the reduction in the expansion pressure.

(4) In the case entire surface heating, the residual adhesive strength of the concrete is significantly reduced because cracks continuously occur along the rebar and around the rebar.

(5) There were no significant differences caused by the watercement ratio. The volume of the voids increases greatly from the dehydration of the gel or capillary water, decomposition of calcium hydroxide, and from the evaporation of bound water.

(6) The heat conductivity of the rebar decreases as its diameter increases. As the surface area increases, there is greater heat loss in the heat transfer coefficients, which in turn decreases the rebar's expansion forces.

(7) If cracks occur because of the expansion pressure of the rebar, most of the cracks are generated at the rebar rib and extend to the surface of the rebar. As a result, the stress and hence the residual adhesive strength decrease.

(8) By using high-frequency induction heating, selective heating is possible, and the dismantling of a ferroconcrete member of a structural framework can be achieved by the induction of cracks and the reduction of the residual adhesive strength.

(9) If the ferroconcrete is disassembled using the technique in this study, complete separation of the rebar and the concrete would be possible, minimizing the required cost and energy for 2^{nd} stage sorting. Also, it can help to simplify the processes involved in the aggregate recycling system such as the separation and recycling of the internal metal parts.

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