THE CORROSION OF REINFORCEMENT IN CONCRETE

by

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INTRODUCTION

Corrosion is the destruction of metal by chemical or electrochemical action.

In the study of corrosion during the past sixty years, several theories have been advanced, all of which account for certain observed corrosion phenomena, but it was not until recognition of the fact that most corrosion reactions are electrochemical, and that films play a very important part in determining the rate and distribution of corrosion, that a satisfactory explanation of corrosion was found.

Concrete bridges, viaducts, retaining walls, and tunnels may be seriously injured by the return current of electric railways, especially when subjected to leakage from sewers and gas pipes or to surface drainage from streets.

Some research was done at the beginning of this century on corrosion of reinforcements embedded in concrete. This stopped without further investigation, but in recent years work was begun again on this problem. For example, the greater portion of the injury is evidenced by deep cracks in the concrete parallel to the reinforcing rods, which in some places were as much as six inches from the surface of the concrete. These cracks appeared only in portions of the building or any concrete structures where the concrete was wet and where the reinforcement had a positive electrical charge which decomposed the moisture and released nascent oxygen on the surface of the rods. This produced a dense layer of iron oxide which required more room than

the iron, the consequent expansion therefore forced the concrete asunder.

Included in this thesis are some photographs taken by Professor C. H. Scholer illustrating the damage to the concrete affected by the corrosion of the reinforcement (Plates I and II). The electrochemical theory of corrosion proposes that corrosion of iron is largely accomplished by the action of a network of short-circuited electrolytic cells on the iron surface. Iron ions go into solution at the anodes of these cells in amounts chemically equivalent to the reaction of the cathodes.

At the anode areas of an iron surface, the reaction is:

$$\underset{\text{Metal}}{Fe} = \underset{\text{ions}}{Fe^{++}} + \underset{\text{electrons}}{2e^-} \qquad 1$$

At the cathode area the following reaction takes place:

$$\underset{\text{atoms}}{2H^+} + \underset{\text{dissolved}}{\tfrac{1}{2}O_2} + \underset{\text{electrons}}{2e^-} = \underset{\text{liquid}}{H_2O} \qquad 2$$

Oxygen and moisture are the basic factors necessary for the corrosion of iron. If a piece of iron is kept dry, it will not rust in contact with air; if it is kept out of contact with air, it will not rust even though it is in contact with water. This leads to the conclusion that atmospheric rusting is a two-stage process involving first, reaction of iron with water to form $Fe(OH)_2$ and H_2,

$$Fe + H_2O = Fe(OH)_2 + H_2$$
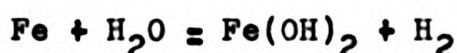
and second, the subsequent oxidation of the $Fe(OH)_2$ to hydrated Fe_2O_3 and the H_2 to H_2O. Oxidation of the H_2 to H_2O removes the

film of hydrogen gas and keeps the iron exposed to the air and
moisture.

$$4 \ Fe(OH)_2 + O_2 + H_2O = 2 \ Fe_2O_3 \cdot X \ H_2O \quad \text{(iron rust)} \\ \text{(reddish-brown)}$$
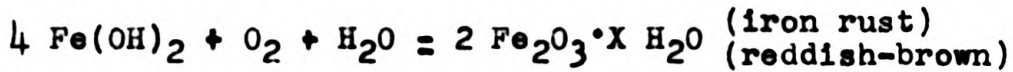
The presence of salt in the moisture or the water acceler-
ates the rusting. In this research, in case of anodic action,
the steel bar in the concrete cylinder acts as anode, the iron
shell around the cylinder acts as cathode, and the salt solution
as electrolyte.

The two reaction products are ferrous ions at the anode and
hydrogen ions are changed to hydrogen atoms at the cathode. The
final result at the anode area will be hydrated iron oxide, due
to the presence of iron, oxygen, and water.

PURPOSE

The purpose of this research is to study the behavior of
the concrete during the corrosion of the reinforcement and dur-
ing the cathodic protection of the reinforcement, and to study
the ability of concrete to withstand the expansion accompanying
the corrosion of the reinforcing bar without cracking.

REVIEW OF LITERATURE

Rosa, McCollum, and Peters (24) stated that the concrete
did not lose or decrease its strength after the reinforcement
bar had been badly corroded and the crack appeared in the con-
crete. They said, "There is no indication whatever that the
cement decayed or deteriorated in any way as reported by some

earlier investigators, but on the contrary the appearance of the concrete, and its mechanical properties, both indicate very strongly that there has been no such action." For waterproofing the concrete, Brown (4) said, "I have carefully tried various oils, asphalts, stearates, resinates, etc., for waterproofing concrete, but do not find any of them to stand up under the severe tests which I have described."

The process of coating the concrete by some waterproofing material to prevent corrosion stated by Brown when he said (4), "Permanent protection from electrolysis cannot be secured by painting or by coating a concrete structure with a membrane and waterproof material. These will sooner or later hydrolize, or crack from settlement of structure, or disintegrate from action of gas liquor in the water. A leak may then occur at a long distance from the spot where the waterproof layer has failed, and destruction follow in unsuspected places."

Rosa, McCollum, and Peters (24) found that in the cathodic protection, the concrete layer surrounding the steel bar had been disintegrated. They studied the cause of this softening and they found that all the specimens which had been tested contained considerable amounts of sodium and potassium in soluble form. When current passed through the specimen these alkalies were gradually concentrated near the negative terminal and in time the concentration of the alkali became sufficient to attack the cement, the principal reactions being the replacement of the calcium in the calcium silicate and aluminates by sodium or potassium silicates and aluminates, and the formation of calcium

hydroxide.

Rosa, McCollum, and Peters (24) in their research found that the resistance of the concrete increased gradually with time as electric current passed through reinforced concrete in the laboratory. They found also that the increase in resistance was at the surface of the concrete nearest the cathode.

Nicholas (19) made tests on steel pipes embedded in concrete cylinders and stated that the cracks occurring in the concrete after passing a direct current through were due to the gaseous pressure theory, which states that the steel pipe anode liberated two gases at its surface, viz., oxygen and chlorine. If these gases were hindered in their escape by the surrounding concrete, they would accumulate and gradually increase in pressure. As the pressure increased the gases would penetrate into the voids. As the pressure in a particular void increased, the surrounding cement crystals would be subjected to a tensile stress - a stress which they are least able to withstand, and might reasonably crack. The minute crack thus formed would allow the gas to penetrate into the next void and there repeat the same action. Nicholas mentioned the cause of the increase of the resistance of the specimen as being due to a film of gas that would form around the steel anode and thus interpose a relatively high resistance in the path of the current.

Rosa, McCollum, and Peters (24) have done research on cathodic protection. They stated, "Throughout the tests with iron cathodes, water was forced out around the embedded iron and kept the top of the specimen wet. This forcing out of water was

evidently due to the formation of gas at the cathode, which, on escaping, forced the water through the pores of the concrete to the surface. This water carried calcium hydroxide in solution and as evaporation took place, calcium carbonate was deposited in rings surrounding the cathode on the surface of the concrete. The greater part of the gas evolved was hydrogen."

Harold P. Brown (4) stated that the mass concrete disintegrates when there is water in it and it is subjected to a heavy flow of electrical direct current of more than 1.5 volts. He found that the calcium silicate and aluminum silicate, which are compounds of the concrete, will decompose when the above condition occurs and the silicic acid appearing with the oxygen, which are the results of the decomposition, will accumulate at the positive pole, while the calcium hydroxide and aluminum hydroxide are carried to the negative pole.

R. I. Perry (23) did a paper on the prevention of corrosion of lead-sheathed power cables in concrete tunnels in which he stated that the cause of the corrosion of the lead sheaths is the calcium hydroxide $Ca(OH)_2$ present in concrete due to its formation in the hydration of Portland cement. Concrete which has been exposed to the air sufficiently long to bring about complete carbonation of the hydroxide at the outer surfaces will in most cases have little effect on lead which may come in contact with these surfaces. Water flowing over well cured concrete will usually absorb very little calcium hydroxide, but water seeping through concrete will do so to some extent and may even become saturated. Water containing a sufficient amount of

calcium hydroxide will corrode lead. To prevent this corrosion, Mr. Perry said, "The cable operating record of this utility company shows that lead power cables may be operated in continuous concrete ducts and in ducts of other non-metallic materials encased in concrete and located in wet tunnels without serious corrosion due to calcium hydroxide."

Dr. Speller (30) stated in his book some facts about corrosion, and he mentioned that when iron corrodes in the atmosphere the amount of ferrous rust produced is small, but when formed under water the corrosion products often contain a large proportion of ferrous iron. Also, he mentioned the fact that the smaller the anodic areas in relation to the associated cathodic areas, the greater is the rate of penetration of corrosion at the anodic points.

Ham (12) designed some instruments for measuring the corrosion current. Practically all DC instruments used in corrosion measurements are the D'Arsonval type. The DC D'Arsonval instrument basically is a current sensitive device. It may be arranged to measure either current or voltage. The mathematics underlying this type of instrument show that for a given spring constant, the instrument has a resulting power sensitivity which is independent of the number of turns on the moving coil or the resistance of the moving coil, provided the physical dimensions of the instrument remain the same. Instruments having higher sensitivity, that is, lower power consumption, are characterized by weaker spring torque and consequently, lower torque-weight ratio. Since the torque-weight ratio is a measure of the instrument's

ruggedness, it can be seen easily that the higher sensitivity instruments are not particularly rugged. An example of this relationship between ruggedness and power sensitivity is Mr. Ham's classification of the instruments into three groups. The first group, called super-sensitive, designates instruments having power sensitivity in the region of 0.1 to 1.0 microwatt. The second group, sensitive field, is instruments having power sensitivities in the order of 10.0 microwatts. The third group field, designates instruments for rugged service which take approximately 100.0 microwatts of power in the basic range. In addition to the basic instruments described, Mr. Ham designed special circuits to increase effective sensitivity of the various instruments without causing excessive mechanical delicacy. One of these is the potentiometer voltmeter. This instrument uses a rugged voltmeter or millivoltmeter to give the actual indication, but really depends on a galvanometer for its high sensitivity. In this way, the deflection power for the main instrument is obtained from an internal power source whereas the sensitivity for the instrument is obtained from a galvanometer whose accuracy need not be high. Another special circuit instrument is the zero-resistance current meter. The deflecting power of the main instrument is obtained from internal batteries and the ultimate sensitivity of the instrument is obtained from a galvanometer.

MATERIALS USED

The following materials were used in making the specimens:

Type I Portland cement with a commercial name (Lonestar). The specific gravity of the cement was 3.15. The cement was brought from Bonner Springs, Kansas.

The Ottawa sand used has a sieve analysis passing a three-quarter inch sieve and retained on #50 sieve. The unit weight was 111.4 pounds per cubic foot, with specific gravity of 2.63.

A broken stone passing through a one-half inch sieve and retained on a #8 sieve with the specific gravity of 2.44 and a unit weight of 101.8 pounds per cubic foot, was used in making the concrete of some of the large cylinders.

The properties of the mentioned materials are listed on separate sheets.

The water used was a distilled water for making the concrete and for the curing also, except for some salt added for certain purposes. About six gallons per sack of water was used in mixing the concrete.

Seventeen samples of different Lignosite from Puget Sound Pulp & Timber Company, Bellingham, Washington, were used as admixture for the concrete. One gram, one and one-half grams, two grams, two and one-half grams, and three grams of each sample were tested according to ASTM C-109, Mortar Testing Procedure. More than a hundred specimens were tested with these admixtures to find the best admixture, the one which gives the highest strength to the concrete. Three specimens for each test were casted, and cured in the distilled water for periods of three days, seven days, and fourteen days.

The workability and strength test of the specimens to which

these admixtures were added are shown in Table 17.

The experiments showed that the best admixture was No. 1493. Thus this admixture was used with one group of the large cylinders to study its effect on the concrete when subjected to direct current.

Two kinds of coating materials were used. The first material consisted of two semi-liquid compounds, SIKAEPOXY BONDING COMPOUND 165A, and SIKAEPOXY BONDING COMPOUND 165B. The mixing ratio by weight of the two compounds was 16 of compound A to 25 of compound B.

The other waterproof coating material used also consisted of two compounds. The first compound was semi-liquid, FIBER GLASS, and the other compound was a liquid called EVER COAT SETTING AGENT #2. The mixing ratio between the two compounds was one oz. of EVER COAT to ten drops of SETTING AGENT #2.

Another material used as admixture was sent from The West Virginia Pulp and Paper Company. It had the company number XW-1-INDULIN. This compound was in a powder form. This admixture is supposed to make the concrete impervious when mixed with the admixture and so prevent the corrosion of the reinforcement embedded in the concrete.

SAND

SIEVE ANALYSIS:

Total Wt. is 500.0 Grm.

Sieve size	Wt. ret.(Grm.)	Wt. pass(Grm.)	% pass
1.5"	0.0	500.0	100.00
3/4"	0.0	500.0	100.00
3/8"	6.0	494.0	98.80
#4	14.1	485.9	97.18
#8	37.4	462.6	92.52
#16	134.0	366.0	73.20
#30	267.2	232.8	46.56
#50	414.7	85.3	17.06
#100	487.1	12.9	2.58
Pan	496.8	3.2	0.64

DENSITY:

1) Vol. of container is 1/10 cu. ft.

2) Wt. of container is 2666.0 Grm.

3) Wt. of cont. & Wt. of comp. sand is 7718 Grm.

4) Wt. of sand only is 5052 Grm.

5) Density of sand is 111.4 p.c.f.

SPECIFIC GRAVITY:

1) Wt. of pyc. is 316.5 Grm.

2) Wt. of pyc. & Wt. of sand is 816.5 Grm.

3) Wt. of sand only is 500.0 Grm.

4) Wt. of pyc. & Wt. of sand & Wt. of water is 1135.9 Grm.

5) Wt. of pyc. & Wt. of water is 828.2 Grm.

6) Displacement is 192.3 Grm.

7) Specific gravity of sand = 500.0/192.3 = 2.63

% ABSORBTION:

5.5%

BROKEN STONE

SIEVE ANALYSIS:

Total Wt. is 1000.0 Grm.

Sieve size	Wt. ret.(Grm.)	% retained	% pass
1/2"	153.0	15.3	84.7
3/8"	608.0	60.8	39.2
#4	813.0	81.3	18.7
#8	924.0	92.4	7.6
#16	973.0	97.3	2.7
#50	998.0	99.8	0.2
#100	1000.0	100.0	0.0

DENSITY:

1) Vol. of container is 1/2 cu. ft.

2) Wt. of container is 10.3#

3) Ave. wt. of container & wt. of broken stone is 61.2#

4) Ave. wt. of comp. broken stone is 50.9#

5) Density of the broken stone is 101.8 p.c.f.

SPECIFIC GRAVITY:

1) Wt. of pan is 227.0 Grm.

2) Wt. of pan & wt. of b. stone is 1272.0 Grm.

3) Wt. of broken stone only is 1045.0 Grm.

4) Wt. of the b. stone in water is 617.0 Grm.

5) Displacement is 428.0 Grm.

6) Specific gravity of b. stone = 1045.0/428 = 2.44

% ABSORBTION:

1%

WORK AND DISCUSSION

Two groups of large size concrete cylinders (five inches diam. x eight inches high) of the same mixing proportions were subjected to six constant voltage of direct current supplied from a battery charger. The voltage was adjusted by a small potentiometer connected to the steel bar every day before reading the current. Three of these cylinders were tested at the same time. These cylinders were set in clay jars of nine inch inside diameter by ten inch height. A layer of sand under the concrete cylinders allowed the bottom face of the cylinder to be submitted to the electrolyte. No. 24 gauge sheet iron was rolled into a cylinder eight inches in diameter by nine inches high and placed around the specimen. These iron shells around the concrete cylinders were at a distance of two inches from the concrete cylinders. Three per cent brine filled the space between the concrete cylinders and the jar wall. The upper faces of the concrete cylinders were dry all the time. The one inch iron bar of 12 inch length was surrounded by a three inch concrete layer on all outside surfaces and bottom. The reason for the three inch layer of the common concrete cover is to similate the cover of the reinforcement of the practical construction. The first group of different mixing ratios were as anode effects, or those effects observed where the current flows from the embedded iron out into the concrete through the electrolyte to the iron shell around the concrete cylinders which acts as cathode. The current amounts were recorded every day at certain times after

adjusting the voltage.

The other group was as cathode effects, or those occurring
when the current flows from the iron shell through the water
solution (electrolyte) and the concrete to the iron bar. This
test was done by reversing the direction of the current, i.e.,
the iron shell around the concrete cylinder as anode and the
iron bar embedded in concrete as cathode. In the first group
the iron bar corroded and cracks occurred in the concrete, while
in the second group the iron shell corroded and nothing happened
to the iron bar or to the concrete.

The different mixing proportions of the large size concrete
cylinders were given a laboratory number of "V" for the anode
effects, or the rust accumulated around the iron bar, and "C"
number for the cathode effects, or the rust accumulated on the
iron shell. They were as follows:

(a) V_1 & C_1: Neat cement without salt. The amount of
water used was 28 per cent by weight which gave a good hardening
test fit the specification. The first hardening was after two
hours and 50 minutes and the second hardening was after four
hours and 30 minutes. The consistancy test of the neat cement
was 27 which fit the specification. The curing time was 28 days.

(b) V_2 & C_2: Concrete specimens of mixing property of one
cement to one sand without salt. (1:1) The curing time was 28
days.

(c) V_3 & C_3: Concrete specimen of mixing ratio of one
cement to two and three-quarter sand without salt (1:2.75).
This specimen has more sand than the last one. The reason for

this is to study the behavior of reinforced concrete subjected to current when the amount of sand increases. The specimens were kept in distilled water for 14 days. These cylinders were tested under constant high voltage of 50 volts of direct current. The electrolyte was ten per cent of salt brine.

(d) V_4 & C_4: In these specimens the amount of cement had been tripled compared to V_2 (1:1), i.e., the mixing ratio by weight was three cement to one sand, and free of salt water. These specimens had been kept in distilled water for 28 days. The cylinders were tested under voltage of three times the potential difference between the concrete and steel bars observed in severe cases, which is about 1-2 volts. The specimens were immersed in salt solution of three per cent salt brine.

(e) AV_6 & AC_6: After choosing the best admixture to the concrete after long investigation which was sent by Puget Sound Pulp & Timber Company under the number 1493. The best amount of this admixture found and used was six-tenths per cent of the cement by weight. The ratio of mixture was one cement to two and three-quarter sand to six-tenths admixture. This concrete has the same proportion as V_3 except that the admixture was added here. The admixture is black in color with a strong bad odor and comes in powder form. These specimens were cured in the distilled water for 28 days. The cylinders were tested under constant six volts of direct current.

Another group of large cylinders have been tested. Three different reinforced bars were embedded in three concrete cylinders. The bars are:

1. Nickel coated bar with 0.001 inch thick nickel. The nickel coated #6 steel bar by electrical method. The laboratory number of this specimen was N_1.

2. Nickel coated bar with 0.003 inch thick nickel, i.e., the thickness of coating material (nickel) had been tripled. The laboratory number of this specimen was N_2.

3. Epoxy resin coating: In this bar the epoxy coated the bar then a layer of sand was attached to the epoxy to make a good bonding bar. The laboratory number of this specimen was S.

These bars are supposed to be non-corrodable, thus these bars have been tested to see if they will corrode or not, and to study the behavior of the concrete reinforced by the bars and subjected to direct current.

These specimens were tested under anodic action.

The mixing ratio by weight of this concrete was one cement, to two and one-quarter sand, to two and three-quarter broken stone.

The specimens were kept in water for 14 days, then constant six volts direct current was applied to them. The electrolyte used was three per cent salt brine. The current reading was taken every day after adjusting the voltage, except on Sundays and on holidays.

Sketch of the large specimen is shown in Plate X, Figure 1.

Small specimens of two inch cubes were tested to find the time elapsed before cracking. A #4 plain bar of one inch length was embedded in the concrete as shown in Plate X, Figure 2. Since the cubes were immersed in three per cent salt brine,

insulated wire was punched into the steel bar and epoxy of two parts mixed together equally was placed around the wire to the bar surface to prevent any contact between the insulated wire and the moisture if there is an open part of the wire at that place.

Four groups of these specimens were tested as anodic effect under constant voltage direct current of six volts, or it means the steel bars were connected with the positive wires and the iron plates surrounding the cubes with the negative wires. The electrolyte was three per cent salt brine. The main purpose of these tests is to study the life of these specimens when subjected to direct current. These groups are:

1. The first group (A-0-) made of best mixing ratio between the cement and sand as mentioned in the ASTM specification test (1:2.75). This group contained three specimens with different times of curing in distilled water (3, 7, 14 days). The reason for these different curing times was to see the effect on concrete when kept in water for different periods of time. The reason for 3, 7, and 14 days curing was because these are the most common curing times which give best strength to the concrete. The concrete of these specimens was mixed with distilled water also, to be sure that it was made of free salt. No salt or admixture was added to this group.

2. (A-3) In this specimen a little amount of salt was added, and the other properties were kept as before. Only two specimens of this group were made. The time of curing was three days and seven days. The conditions of casting and curing were

the same as in the last group. The reason for this group was to study the effect of the salt on the concrete under direct current.

3. (A-10-) In this group the amount of salt in the mixture was increased by more than three times. Two specimens of this group were made, with two different curing times. The mixing ratio and condition of casting were the same as before.

4. (A-) This group was made with neat cement without any salt. This group was free from any salt because the water used for mixing was distilled water and the specimens were kept in distilled water for curing.

Another group of small cubes had the same properties as before, but was coated with many different waterproofing materials.

One of the compounds used as coating material was submitted by a chemical company. This compound consisted of two semi-liquid parts, SIKAEPOXY BONDING COMPOUND 165A, and SIKAEPOXY BONDING COMPOUND 165B. The ratio of mixing compound A to compound B by weight was 16 to 25 according to the company directions.

A brush was used for coating. Two layers of coating material were used on the specimens. The second layer was used after the first layer had been completely dry for a couple of days. The reason for the second layer was to fill all the holes missed by the first layer and to provide a good coating. The following groups were coated by this compound:

Ac-, Ac-3-, and Ac-10

These groups had the same mixing ratio and the same curing

conditions as to their corresponding previous numbers except that they were coated by the mentioned waterproofing materials.

Another kind of waterproofing material was composed of two parts: One part was a thick liquid of commercial name <u>FIBERGLASS EVERCOAT</u>, and the other part was a liquid in a small container like an eye drop container, and its name was SETTING AGENT #2. This is a type of polyester resin used in making fiberglass boats. The mixing quantity of the two parts was one ounce EVERCOAT (part one) to ten drops SETTING AGENT #2 (part two). These two compounds must be well mixed. The brush was used for coating the small cubes with this waterproofing compound and two layers of this compound were used.

Only one group (Ac-0-) was coated by this compound. This group has the same mixing ratio (1:2.75:0), and curing time (3, 7, and 14 days) as before. This group of three specimens was enough to provide a good result.

A certain admixture was submitted by The West Virginia Pulp and Paper Company as a corrosion prevention compound when mixed with concrete. The admixture was used to see if it prevents corrosion or not. The company number of this admixture was XW-1-INDULIN. This admixture was in powder form. Two groups of specimens with two amounts of this admixture were used.

The amount of the admixture by weight used in the first group (XW-1-) was three per cent of the cement. The mixing ratio of cement to sand was as the common ratio used before (1:2.75). This group was free from salt.

In the other group the amount of admixture was increased to

0.4 per cent of the cement. The reason was to study the effect of different amount of this admixture on the concrete when subjected to direct current. The amount of the aggregate used in this group and the time of curing were the same as before.

Table 16 shows the laboratory number, mixing ratios, and time of curing of all the specimens which have been tested. The number of the uncoated specimens free of admixture start with the letter A which means that the specimens were under anodic effect, while for the coated specimens the first letter of the laboratory number was Ac, the small letter c designating "coated".

The second mark in the laboratory number after the dash is a number which means the amount of salt in the specimens, because the amount of salt has a big effect on the concrete. For example, the laboratory number A-O- means free of salt because the second number was zero. The last number after the dash means the curing time, i.e., when the last number is three, this means that the specimen was cured for three days.

Constant voltage, direct current of six volts, was applied to the small specimens. The electrolyte was three per cent salt brine.

The purpose of testing the small specimens was to compare the time of the first crack due to the corrosion of the reinforced bar embedded in concrete with different mixing properties, and to determine if the admixture XW-1-INDULIN prevents the corrosion of the reinforcement or not, and how it affects concrete. The purpose of coating these small cube specimens was

to determine whether or not the coating makes the concrete impervious.

The concrete used in these small specimens was tested by ASTMC-109, Mortar Test, to check the workability of the concrete before casting it (Table 17).

APPARATUS

The apparatus used to supply 50 volts of direct current consists of an auto transformer to step 110 volts to 50 volts then rectified to change alternative current to direct current and a voltmeter to read the voltage.

The steel bar in the concrete cylinder represents the anode (+) and is connected to the negative (-) wire coming from the rectifier. The current in amperes is recorded by reading the ammeter.

The iron shell around the concrete cylinder represents the cathode (-) and connected to the negative (-) wire coming from the rectifier. The current flows from the rectifier unit to the anode system then through the electrolyte to the iron shell around the concrete cylinder. The apparatus sketch is shown in Plate VIII.

The apparatus to supply six volts direct current consists of:

1. Battery charger - which supplies direct current of either six volts or twelve volts.

2. Masonite plate - which has four phone jacks.

3. Voltmeter and ammeter - to read the voltage and the

current.

4. Variable resistor - connected to the anode or to the steel bar in the concrete cylinder to control the voltage.

The means of connecting the apparatus to the concrete cylinders and small specimens is to connect the negative pole (-) of the battery charger to the four phone jacks in the masonite plate and connect each iron shell, surrounding the concrete cylinders, which represent the cathode (-) to each appropriately numbered phone jack in the masonite plate. The positive pole of the battery charger was connected to all of the steel bars in the concrete cylinders. The steel bars of the small specimens which represent the anode (positive) were connected to the positive pole of the battery charger. Then the iron shells around the specimens had to be connected to one phone jack in the masonite plate.

The apparatus sketch is shown in Plate IX.

The current was checked by plugging an ammeter into the phone jack for each cell and the voltage was read by connecting the voltmeter across each cell.

TABLES

Table 1. Large concrete cylinders.

No. of specimens tested	Mixing ratio			Laboratory No.	
	cement	sand	b. stone	anodic effect	cathodic effect
2	1	0	0	V_1	C_1
2	1	1	0	V_2	C_2
2	1	2.75	0	V_3	C_3
2	3	1	0	V_4	C_4
2	1	2.75	Admixture	AV_6	AC_6
1	1	2.25	2.75	N_1	-
1	1	2.25	2.75	N_2	-
1	1	2.25	2.75	S	-

Table 2. Mixing amounts of large cylinder specimens.

Specimen No.	Absolute volume (cu. ft./sack)				Weight (#/sack)				Total volume (cu.ft./sack) (A)	Ratio* B/A	Weight (#/specimen)				
	cement	sand	broken stone	water	cement	sand	broken stone	water			cement	sand	broken stone	water	admixture
V_1	0.48	0	0	0.83	94.0	0	0	52.0	1.31	0.099	9.3			5.15	
V_2	0.48	0.68	0	0.80	94.0	111.4	0	50.0	1.96	0.067	6.3	7.5		3.35	
V_3	0.48	2.06	0	0.80	94.0	314.0	0	50.0	3.34	0.039	3.7	12.2		1.95	
V_4	1.43	0.68	0	0.80	282.0	111.4	0	50.0	2.91	0.044	12.4	4.9		2.200	
AV_6	0.48	2.06	0	0.79	94.0	314.0	0	49.0	3.33	0.039	3.7	12.2		1.91	1.0×10^{-5}
N_1	0.48	1.52	1.84	0.80	94.0	250.0	280.0	50.0	4.64	0.028	2.6	7.0	7.8	1.400	
N_2	0.48	1.52	1.84	0.80	94.0	250.0	280.0	50.0	4.64	0.028	2.6	7.0	7.8	1.400	
S	0.48	1.52	1.84	0.80	94.0	250.0	280.0	50.0	4.64	0.028	2.6	7.0	7.8	1.400	
C_1	0.48	0	0	0.83	94.0	0	0	52.0	1.31	0.099	9.3			5.15	
C_2	0.48	0.68	0	0.80	94.0	111.4	0	50.0	1.96	0.067	6.3	7.5		3.35	
C_3	0.48	2.06	0	0.80	94.0	314.0	0	50.0	3.34	0.039	3.7	12.2		1.95	
C_4	0.48	0.68	0	0.80	282.0	111.4	0	50.0	2.91	0.044	12.4	4.9		2.20	
AC_6	0.48	2.06	0	0.79	94.0	314.0	0	49.0	3.33	0.039	3.7	12.2		1.91	1.0×10^{-5}

* Volume of one specimen (B) is 0.129 cu. ft.

Table 3. Current measurements of laboratory specimen V_1.

Date	Time	Current (M.A.)	Resistance (Ohms)	Remarks
4-18-60	11:00 A.M.	70.0	85.7	Bubbles of gas escaped between steel bar and concrete.
19	" "	44.0	136.4	
20	" "	41.5	144.6	
21	" "	46.5	129.1	
22	" "	38.0	157.9	Rust around the steel bar.
23	" "	36.0	166.7	
24	4:30 P.M.	Did not read		Very fine crack.
25	2:00 "	59.0	101.7	
26	11:00 A.M.	64.5	93.0	Three fine cracks radially.
27	" "	64.5	93.0	Fourth crack happened. Enlarging the other cracks. Ampere arrow swinging between 63.5 and 64.5 milliamperes.
28	" "	65.5	91.6	Big bubble of yellow semi-liquid material on the connection of the steel bar with the concrete.
29	" "	65.5	91.6	
30	" "	67.5	89.0	The rust moved on the surface of the concrete and reached the electrolyte.
5-1-60	" "	62.5	96.0	End of experiment.

Table 4. Current measurements of laboratory specimen V_2.

Date	Time	Reading (M. A.)	Resistance (Ohms)	Remarks
4-19-60	11:00 A.M.	55.0	109.0	
20	" "	43.5	138.0	
21	" "	40.5	148.1	Rust around the steel bar.
22	" "	46.5	129.0	
23	" "	44.0	136.2	
25	2:00 P.M.	41.5	144.5$\frac{1}{4}$	
26	11:00 A.M.	37.0	162.2	
27	" "	34.5	174.0	White salt on the anode (-) and on top surface of the concrete.
28	" "	36.5	164.4	
29	" "	35.0	171.8	
30	" "	33.5	179.4	
5-2-60	" "	28.0	214.0	
3	" "	31.0	193.5	
4	" "	28.5	211.0	
5	" "	28.0	214.0	
6	" "	27.5	217.8	
7	" "	24.5	245.0	
9	" "	22.0	273.0	
10	" "	21.5	279.0	
11	" "	21.0	286.0	
12	" "	32.5	184.5	Water on top surface of the concrete.
13	" "	26.0	231.0	
14	" "	25.0	240.0	
16	" "	26.5	226.0	
17	" "	27.5	218.0	
18	" "	26.0	231.0	
19	" "	36.0	166.8	
20	" "	31.0	193.5	
21	" "	30.0	200.0	
23	" "	28.5	211.0	
24	" "	42.0	143.0	
25	" "	37.0	162.2	
26	" "	32.0	187.4	
27	" "	29.0	207.0	
28	" "	28.0	214.0	
30	" "	27.0	222.4	
31	" "	26.0	231.0	
6-1-60	" "	26.0	231.0	
2	" "	26.0	231.0	
3	" "	26.0	231.0	
4	" "	30.0	200.0	Water added.
6	" "	24.0	250.0	

Table 4 (concl.).

Date	Time	Reading (M. A.)	Resist- ance (Ohms)	Remarks
6-7-60	11:00 A.M.	24.0	250.0	
8	" "	26.0	231.0	
9	" "	25.0	240.0	
10	" "	25.0	240.0	
11	" "	25.0	240.0	
13	" "	26.0	231.0	
14	" "	27.0	222.4	
15	" "	33.0	182.0	
16	" "	35.0	171.3	
17	" "	36.0	166.8	
20	" "	36.0	166.8	
21	" "	37.0	162.2	
22	" "	36.0	166.8	
23	" "	36.0	166.8	
24	" "	35.0	171.3	
25	" "	34.0	176.5	
27	" "	73.0	82.2	First crack happened. End of experiment.

Table 5. Current measurements of laboratory specimen V_3.

Date	Time	Current (Amp.)	Resist-ance (Ohms)	Temp. of electrolyte	Remarks
3-30-60	3:00 P.M.	1.4	35.6	40 F.	Gases escaped from electrolyte and between iron bar and concrete.
30	5:15 P.M.	1.3	38.5		
31	7:45 A.M.	0.6	83.3		
31	1:30 P.M.	0.55	91.0		First crack.*
31	3:00 P.M.	0.55	91.0	92 F.	Crack enlarged, specimen heated, electrolyte heated, salt accumulated on concrete surface. Depth of the longitudinal crack was 6". End of experiment.

* First crack happened in 22.5 hours.

Table 6. Current measurements of laboratory specimen V_4.

Date	Time	Current (M. A.)	Resistance (Ohms)	Remarks
5-2-60	11:00 A.M.	47.0	127.7	
3	" "	39.0	153.8	
4	" "	36.0	166.7	
5	" "	38.0	157.9	
6	" "	37.0	162.2	
7	" "	32.5	184.6	
9	" "	28.5	210.5	
10	" "	29.0	206.9	
11	" "	30.5	196.9	
12	" "	20.0	300.0	
13	" "	19.0	315.8	
14	" "	24.0	250.0	
16	" "	25.0	240.0	
17	" "	23.5	255.3	
18	" "	23.5	255.3	
19	" "	24.0	250.0	
20	" "	24.0	250.0	
21	" "	23.5	255.3	
23	" "	23.0	260.9	
24	" "	26.0	230.8	
25	" "	25.5	235.3	
26	" "	22.0	272.7	
27	" "	21.0	285.7	
28	" "	20.0	300.0	
30	" "	20.0	300.0	
31	" "	21.0	265.7	
6-1-60	" "	22.0	272.7	
2	" "	22.5	266.7	
3	" "	22.5	266.7	
4	" "	23.0	260.9	Water added.
6	" "	24.0	250.0	
7	" "	20.0	300.0	
8	" "	18.0	333.3	
9	" "	20.0	300.0	
10	" "	22.0	272.7	
11	" "	23.0	260.9	
13	" "	24.0	250.0	
14	" "	25.0	240.0	
15	" "	28.0	214.3	Four cracks. End of experiment.

Table 7. Current measurements of laboratory specimen AV$_6$.

Date	Time	Current (M. A.)	Resistance (Ohms)	Remarks
5-4-60	11:00 A.M.	68.5	87.8	Water on top of concrete surface.
5	" "	39.0	154.0	
6	" "	37.5	160.0	
7	" "	35.0	171.3	
9	" "	30.0	200.0	
10	" "	30.0	200.0	
11	" "	34.0	176.5	
12	" "	37.0	162.2	Water on top of concrete surface.
13	" "	25.0	240.0	
14	" "	25.0	240.0	
16	" "	26.0	231.0	
17	" "	24.5	245.0	
18	" "	24.5	245.0	
19	" "	25.0	240.0	
20	" "	23.5	255.0	
21	" "	24.0	250.0	
23	" "	25.0	240.0	
24	" "	28.0	214.0	
25	" "	27.0	222.4	
26	" "	24.5	245.0	
27	" "	24.0	250.0	
28	" "	24.0	250.0	
30	" "	24.0	250.0	
31	" "	24.0	250.0	
6-1-60	" "	25.0	240.0	
2	" "	25.0	240.0	
3	" "	25.0	240.0	
4	" "	26.0	231.0	Water added.
6	" "	25.0	240.0	
7	" "	23.0	261.0	
8	" "	23.0	261.0	
9	" "	23.0	261.0	
10	" "	23.0	261.0	
11	" "	24.0	250.0	
13	" "	24.0	250.0	
14	" "	24.0	250.0	
15	" "	24.0	250.0	
16	" "	27.0	222.4	
17	" "	27.0	222.4	
20	" "	27.0	222.4	Cracked. End of experiment.

Table 8. Current measurements of laboratory specimen C_1.

Date	Time	Current (M. A.)	Resist-ance (Ohms)	Remarks
2-18-61	12:00 A.M.	55	109	
20	5:00 P.M.	51	118	
21	" "	48	125	Increasing the rust.
22	" "	53	113	
23	" "	56	107	
24	" "	53	113	
25	12:00 A.M.	46	130	
27	5:00 P.M.	53	113	Rust moving on the brine surface.
28	" "	53	113	
3-1-61	" "	55	109	Rust reached the concrete cylinder.
2	" "	57	105	
3	" "	57	105	
4	12:00 A.M.	57	105	
6	5:00 P.M.	57	105	
7	" "	57	105	
8	" "	55	109	
9	" "	52	115	
10	" "	51	118	
11	12:00 A.M.	51	118	
13	5:00 P.M.	51	98	
14	" "	55	109	
15	" "	50	120	End of experiment.

Table 9. Current measurements of laboratory specimen C_2.

Date	Time	Current (M. A.)	Resistance (Ohms)	Remarks
2-18-61	12:00 A.M.	41	146	Rust on iron shell.
20	5:00 P.M.	39	152	
21	" "	39	152	
22	" "	43	140	
23	" "	45	133	
24	" "	43	140	
25	12:00 A.M.	39	152	
27	5:00 P.M.	45	133	
28	" "	53	113	
3-1-61	" "	56	107	
2	" "	53	113	
3	" "	53	113	
4	12:00 A.M.	50	120	
6	5:00 P.M.	50	120	
7	" "	47	128	
8	" "	50	120	
9	" "	49	121	
10	" "	47	128	
11	12:00 A.M.	46	130	
13	5:00 P.M.	54	111	
14	" "	47	128	
15	" "	43	140	End of experiment.

Table 10. Current measurements of laboratory specimen C_3.

Date	Time	Current (Amp.)	Resist- ance (Ohms)	Remarks
3-31-61	3:10 P.M.	1.0	50.0	Hydrogen gas escaped between electrode and concrete.
31	3:25 "	1.4	35.6	
31	4:00 "	1.7	29.4	The concrete and the solution heated.
31	4:45 "	2.0	25.0	
4-1-61	7:40 A.M.	1.2	41.6	Rust on the anode.
1	10:00 "	1.0	50.0	
1	11:00 "	0.95	52.6	
1	1:00 P.M.	0.70	71.5	
2	9:00 A.M.	0.30	166.5	The voltmeter shaking and a sound coming from the battery. Concrete and solution were cold.
2	10:15 "	0.90	55.6	Water added on top surface of the concrete.
2	10:20 "	0.60	83.4	The water on the surface of the concrete drying.
2	12:00 "	0.50	100.0	Temperature increased.
4	9:00 "	0.10	500.0	
4	10:00 "	1.20	41.6	Water added on top surface of the concrete.
4	11:30 "	0.50	100.0	Water dried from the surface.
4	2:00 P.M.	0.40	125.0	
5	10:00 A.M.	0.20	250.0	
5	3:15 P.M.	6.00	8.3	Water added above the concrete surface till it attached the steel bar. The solution boiled near the steel bar where the temp. is 160° F., while it is 85° F. in the solution.
5	3:20 "	0.80	62.6	The water dried from the concrete surface.
6	9:20 A.M.	0.20	250.0	
6	11:00 "	0.18	278.0	
6	1:30 P.M.	0.10	500.0	
7	10:00 A.M.	0.10	500.0	
8	" "	0.10	500.0	
9	9:30 "	0.06	834.0	
14	4:00 P.M.	0.04	1250.0	
15	10:00 A.M.	0.10	500.0	
18	9:30 "	0.04	1250.0	

Table 10 (concl.).

Date	Time	Current (Amp.)	Resist-ance (Ohms)	Remarks
4-19-61	11:00 A.M.	0.04	1250.0	
20	" "	0.04	1250.0	
21	" "	0.10	500.0	
22	" "	0.10	500.0	
23	" "	0.10	500.0	
25	2:00 P.M.	0.10	500.0	
26	11:00 A.M.	0.10	500.0	
27	" "	0.10	500.0	
28	" "	0.10	500.0	
29	" "	0.10	500.0	
30	" "	0.30	166.4	End of experiment.

Table 11. Current measurements of laboratory specimen C₄.

Date	Time	Current (M. A.)	Resist- ance (Ohms)	Remarks
2-18-61	12:00 A.M.	51	118	Rust on iron shell.
20	5:00 P.M.	47	128	
21	" "	47	128	
22	" "	53	113	
23	" "	54	111	
24	" "	52	115	
25	12:00 A.M.	45	133	
27	" "	51	118	
28	" "	51	118	
3-1-61	" "	54	111	
2	" "	56	107	
3	" "	55	109	
4	" "	55	109	
6	" "	54	111	
7	" "	49	121	
8	" "	51	118	
9	" "	50	120	
10	" "	49	121	
11	" "	48	125	
13	" "	40	150	
14	" "	47	128	
15	" "	43	140	End of experiment.

Table 12. Current measurements of laboratory specimen AC₆.

Date	Time	Current (Amp.)	Resist- ance (Ohms)	Remarks
2-18-61	12:00 A.M.	0.275	182.0	Rust on iron shell. White salt on the concrete sur- face.
20	5:00 P.M.	0.250	200.0	
21	" "	0.200	250.0	
22	" "	0.225	225.5	
23	" "	0.225	225.5	
24	" "	0.200	250.0	
25	12:00 A.M.	0.175	286.0	
27	5:00 P.M.	0.175	286.0	
28	" "	0.175	286.0	
3-1-61	" "	0.175	286.0	
2	" "	0.175	286.0	
3	" "	0.175	286.0	
4	12:00 A.M.	0.175	286.0	
6	5:00 P.M.	0.175	286.0	
7	" "	0.175	286.0	
8	" "	0.050	1000.0	
9	" "	0.050	1000.0	
10	" "	0.160	312.5	
11	12:00 A.M.	0.160	312.5	
13	5:00 P.M.	0.175	286.0	
14	" "	0.175	286.0	
15	" "	0.150	333.0	
16	" "	0.150	333.0	
17	" "	0.150	333.0	
18	" "	0.150	333.0	
20	" "	0.150	333.0	
22	" "	0.950	52.5	The temperature jumped to maximum. The temperature of the electrolyte 85° F. The voltmeter arrow shak- ing, whistling sound com- ing from the steel bar. After 5 minutes the cur- rent dropped to 0.55 amp- ere. During these 5 min- utes one-fourth of the wa- ter in the electrolyte evaporated.
23	" "	0.225	222.5	
24	" "	0.275	187.0	
25	12:00 A.M.	0.425	117.0	End of experiment.

Table 13. Current measurements of laboratory specimen N_1.

Date	Time	Current (M. A.)	Resist-ance (Ohms)	Remarks
3-16-61	5:00 P.M.	20	300.0	
17	" "	19	315.8	
18	" "	19	315.8	
20	" "	19	315.8	
22	" "	17	352.9	
23	" "	19	315.8	
24	" "	21	285.7	White salt on concrete surface and on iron shell.
25	12:00 A.M.	21	285.7	
27	5:00 P.M.	22	272.7	
28	" "	21	285.7	
29	" "	19	315.8	Green crystles around the steel bar.
30	" "	42	142.9	No crack appeared, but the green crystles around the steel bar increased. Iron shell corroded in five places, and the rust reached the electrolyte.
31	" "	20	300.0	
4-1-61	12:00 A.M.	19	315.8	
3	5:00 P.M.	21	285.7	White salt accumulated on the top edge of the iron shell, increasing the rust spots on the iron shell.
4	" "	19	315.8	
5	" "	21	285.7	
6	" "	18	333.3	
10	" "	17	352.9	
11	" "	17	352.9	Reddish spots on the concrete surface around the steel bar.
12	" "	16	375.0	
13	" "	16	375.0	
14	" "	18	333.3	
15	12:00 A.M.	16	375.0	
16	5:00 P.M.	29	206.0	First crack. End of experiment.

Table 14. Current measurement of laboratory specimen N_2.

Date	Time	Current (M. A.)	Resistance (Ohms)	Remarks
3-16-61	5:00 P.M.	17	355.9	
17	" "	16	375.0	
18	" "	16	375.0	
20	" "	18	333.3	White salt on concrete surface and on top edge of iron shell. Clean electrolyte.
22	" "	20	300.0	
23	" "	22	272.7	
24	" "	24	250.0	
25	12:00 A.M.	20	300.0	
27	5:00 P.M.	20	300.0	
28	" "	28	214.3	
29	" "	20	300.0	
30	" "	29	206.9	Reddish-brown big spot beside the steel bar, and around this spot, a green-blue spot.
31	" "	19	315.8	
4-1-61	12:00 A.M.	18	333.3	
3	5:00 P.M.	19	315.8	Little amount of white salt on iron shell and concrete surface.
4	" "	18	333.3	
5	" "	20	300.0	
6	" "	18	333.3	
10	" "	28	214.3	Green semi-liquid coming out between steel bar and concrete.
11	" "	27	222.2	
12	" "	31	193.5	
13	" "	29	206.9	
14	" "	35	171.4	First crack happened. Dry green crystles on iron bar and concrete surface. The green semi-liquid became blue and dried. End of experiment.

Table 15. Current measurements of laboratory specimen S.

Date	Time	Current (M. A.)	Resist-ance (Ohms)	Remarks
3-16-61	5:00 P.M.	5	1200.0	
17	" "	6	1000.0	
18	" "	5	1200.0	
20	" "	5	1200.0	White salt crystles on concrete surface.
22	" "	8	750.0	
23	" "	8	750.0	
24	" "	8	750.0	
25	12:00 A.M.	8	750.0	Clean electrolyte.
27	5:00 P.M.	11	545.5	
28	" "	8	750.0	Green spots on the concrete.
29	" "	13	461.5	Hydrogen gas going out from bulbs.
30	" "	8	750.0	
31	" "	10	600.0	
4-1-61	12:00 A.M.	9	666.7	
3	5:00 P.M.	9	666.7	Very little amount of white salt on iron shell and on concrete surface.
4	" "	9	666.7	
5	" "	6	1000.0	
6	" "	8	750.0	
10	" "	8	750.0	
11	" "	26	230.8	Green spot on concrete surface which attaching the electrolyte. Salt on outer surface of the jar in crystle form.
12	" "	3	2000.0	
13	" "	2	3000.0	
14	" "	3	2000.0	
15	12:00 A.M.	3	2000.0	
16	5:00 P.M.	5	1200.0	No crack. End of experiment.

Table 16. Small specimens (2" cubes).

Lab. No.	Mixing ratio by weight				Coated or uncoated	Curing time (days)	Admixture name	Coating Name	Date of starting test	Date of first crack	Life of specimens (days)
	cement	sand	salt	admixture							
A-0-3	1	2.75	0	0	uncoated	3			5-12-60	5-23-60	11
A-0-7	1	2.75	0	0	"	7			5-12-60	6-9-60	28
A-0-14	1	2.75	0	0	"	14			5-13-60	6-2-60	20
A-3-3	1	2.75	0.0144	0	"	3			5-12-60	5-16-60	4
A-3-7	1	2.75	0.0144	0	"	7			5-12-60	5-18-60	6
A-10-3	1	2.75	0.048	0	"	3			5-12-60	5-16-60	4
A-10-7	1	2.75	0.048	0	"	7			5-13-60	5-16-60	3
A-3	Neat cement		0	0	"	3			5-14-60	6-27-60	44
A-7	"	"	0	0	"	7			5-18-60	6-29-60	42
A-14	"	"	0	0	"	14			5-25-60	7-6-60	42
Ac-0-3	1	2.75	0	0	coated	3		Ever Coat	3-22-61	4-1-61	10
Ac-0-7	1	2.75	0	0	"	7		" "	3-22-61	4-7-61	16
Ac-0-14	1	2.75	0	0	"	14		" "	3-22-61	4-14-61	23
Ac-3-3	1	2.75	0.0144	0	"	3		Epoxy	2-17-61	3-8-61	19
Ac-3-7	1	2.75	0.0144	0	"	7		"	2-17-61	3-16-61	27
Ac-3-14	1	2.75	0.0144	0	"	14		"	2-17-61	3-22-61	33
Ac-10-3	1	2.75	0.048	0	"	3		"	2-17-61	3-6-61	17
Ac-10-7	1	2.75	0.048	0	"	7		"	2-17-61	3-8-61	19
Ac-10-14	1	2.75	0.048	0	"	14		"	2-23-61	4-6-61	11
Ac-3	Neat cement		0	0	"	3		"	2-23-61	3-20-61	25
Ac-7	"	"	0	0	"	7		"	2-23-61	3-28-61	33
Ac-14	"	"	0	0	"	14		"	2-23-61	4-6-61	42
XW-1-3	1	2.75	0	0.003	uncoated	3	INDULIN XW-1		3-22-61	4-1-61	10
XW-1-7	1	2.75	0	0.003	"	7	" "		3-22-61	4-5-61	14
XW-1-14	1	2.75	0	0.003	"	14	" "		3-22-61	4-11-61	20
XW-1-A-3	1	2.75	0	0.004	"	3	" "		3-22-61	4-16-61	25
XW-1-A-7	1	2.75	0	0.004	"	7	" "		3-22-61	4-17-61	26
XW-1-A-14	1	2.75	0	0.004	"	14	" "		3-22-61	4-20-61	29

Table 17. Flow test for small specimens concrete in ASTM C-109
            mortar.

Lab. No.	Sand (Grm.)	Cement (Grm.)	Admixture No.	Admixture (Grm.)	Water (C.C.)	Reading
XW-1 (3,7,14,&c)	687.5	250.0	INDULIN XW-1	0.75	110.0	28.0 26.0 26.0 26.0
					Total	104.0
XQ-1-A (3,7,14&c)	687.5	250.0	INDULIN XW-1	1.0	110.0	26.0 25.0 26.0 25.0
					Total	102.0
A (3,7,14&c)	0.0	1500.0		0.0	260.0	28.0 30.0 29.0 27.0
					Total	114.0
A-3 (3,7,14&c)	1375.0	500.0	salt	7.2	240.0	27.0 26.0 26.0 25.5
					Total	105.0
A-10 (3,7,14&c)	1375.0	500.0	salt	24.0	240.0	26.0 27.0 27.0 26.0
					Total	106.0
A-0 (3,7,14&c)	687.5	250.0		0.0	120.0	26.0 25.0 26.0 26.0
					Total	103.0

Table 18. Tests of lignosite in ASTM C-109 mortar.

Cement No.	Admix. No.	Admix. weight (Grm.)	Workability		Compressive strength		
			Water (C.C.)	Reading	3-day	7-day	28-day
C-II		1.0	230	111.0	12,466		26,000
C-II		1.5	220	105.0	15,383		26,166
C-II	E-1395	2.0	215	108.5		11,500	
C-IV		2.5	210	110.5		12,967	
C-IV		3.0	215	113.0		9,533	
C-II		1.0	230	100.0	11,466		23,900
C-II		1.5	220	103.0	14,533		24,300
C-II	E-1396	2.0	220	108.0	10,233		22,100
C-IV		2.5	210	109.0		14,033	24,433
C-IV		3.0	210	108.0		11,667	17,833
C-I		1.0	210	107.8	10,633		21,966
C-I		1.5	210	102.5	9,266		21,733
C-II	E-1442	2.0	210	114.0	10,300		23,266
C-IV		2.5	210	111.0	No strength		
C-IV		3.0	210	111.5			15,300
C-I		1.0	220	113.5	11,200		20,000
C-I		1.5	220	98.0	11,683		22,500
C-II	E-1443	2.0	225	109.5	10,800		22,100
C-IV		2.5	210	114.0		8,500	15,133
C-IV		3.0	210	112.5		11,500	19,100
C-I		1.0	215	111.0	11,166		20,766
C-I		1.5	215	111.5	10,800		21,333
C-II	E-1444	2.0	210	105.5	9,633		19,533
C-IV		2.5	205	108.5		11,967	21,967
C-IV		3.0	205	112.5		7,650	14,567

Table 18 (cont.).

Cement No.	Admix. No.	Admix. weight (Grm.)	Workability		Compressive strength		
			Water (C.C.)	Reading	3-day	7-day	28-day
C-I	Plain	0.0	240	102.5	8,000		22,800
C-I		1.0	220	104.5	10,200		20,066
C-II		1.5	230	99.0	11,233		23,566
	E-1445	2.0	230	111.5	10,833		24,433
C-IV		2.5	210	109.0		12,267	19,333
C-IV		3.0	210	113.0		11,867	21,033
C-III		1.0	240	112.5	9,816		21,933
C-III		1.5	235	109.0	10,300		22,100
C-III	E-1450	2.0	230	115.0			19,100
C-IV		2.5	220	110.0		13,300	
C-IV		3.0	215	111.0		8,334	
C-III		1.0	230	102.0	10,466		22,833
C-III		1.5	230	108.5	12,933 (6 days)		21,966
C-III	E-1451	2.0	215	119.0			19,633
C-IV		2.5	215	111.0			
C-IV		3.0	210	112.0			
C-III		1.0	230	110.5	9,733		20,600
C-III		1.5	230	98.0	13,633 (6 days)		23,400
C-III	E-1452	2.0	220	106.5	10,216		21,333
C-IV		2.5	215	114.0		8,900	
C-IV		3.0	205	112.0		8,933	
C-III		1.0	235	107.0	9,833		21,133
C-III		1.5	235	105.5	12,283		25,133
C-III	E-1453	2.0	235	108.0	10,700		22,666
C-IV		2.5	220	107.0			
C-IV		3.0	220	114.0			

Table 18 (cont.).

Cement No.	Admix. No.	Admix. weight (Grm.)	Workability		Compressive strength		
			Water (C.C.)	Reading	3-day	7-day	28-day
C-II	Plain	0.0	240	98.0	11,466		23,366
C-III		1.0	235	112.0	11,666		23,883
C-III		1.5	235	115.5	12,000		23,600
C-III	E-1454	2.0	230	115.0	9,850		21,216
C-IV		2.5	220	114.0			
C-IV		3.0	215	106.0			
C-III		1.0	235	102.0	12,700 (4 days)		22,333
C-III		1.5	235	101.0	11,000		22,833
C-III	E-1455	2.0	230	98.5	12,200		22,800
C-IV		2.5	220	110.5		17,900	
C-IV		3.0	215	109.0		17,300	
C-III		1.0	235	108.5		20,200	23,466
C-III		1.5	235	109.0	11,616		23,666
C-III	E-1456	2.0	235	112.0	15,116		29,800
C-IV		2.5	220	113.0			
C-IV		3.0	220	115.0			
C-II		1.0	240	100.5	15,833		25,166
C-II		1.5	240	111.0	11,266		22,333
C-II	E-1475	2.0	225	110.0			
C-IV		2.5	220	113.0		16,867 (8 days)	
C-IV		3.0	215	106.5		9,967	
C-IV		1.0	220	107.5		15,167	24,233
C-IV		1.5	220	104.0	9,767		24,000
C-IV	E-1492	2.0	215	102.5	11,300 (4 days)		23,467
C-IV		2.5	215	108.5		10,800	
C-IV		3.0	215	113.0	6,833		22,733

Table 18 (concl.).

Cement No.	Admix. No.	Admix. weight (Grm.)	Water (C.C.)	Reading	3-day	7-day	28-day
C-III	Plain	0.0	240	100.5	11,666		21,833
C-IV		1.0	220	110.5		15,667	
C-IV		1.5	220	112.0	9,933		23,800
C-IV	E-1493	2.0	210	107.5	7,900		23,000
C-IV		2.5	210	108.5		14,367	
C-IV		3.0	210	103.0	9,400		29,500
C-IV		1.0	225	106.0		17,367	
C-IV		1.5	225	103.0	11,700 (4 days)		24,133
C-IV	E-1494	2.0	220	105.0	7,900		15,833
C-IV		2.5	220	107.0		16,667	
C-IV		3.0	215	107.0	7,667		23,300
C-IV	Plain	0.0	240	109.0		15,833	24,767

FIGURES
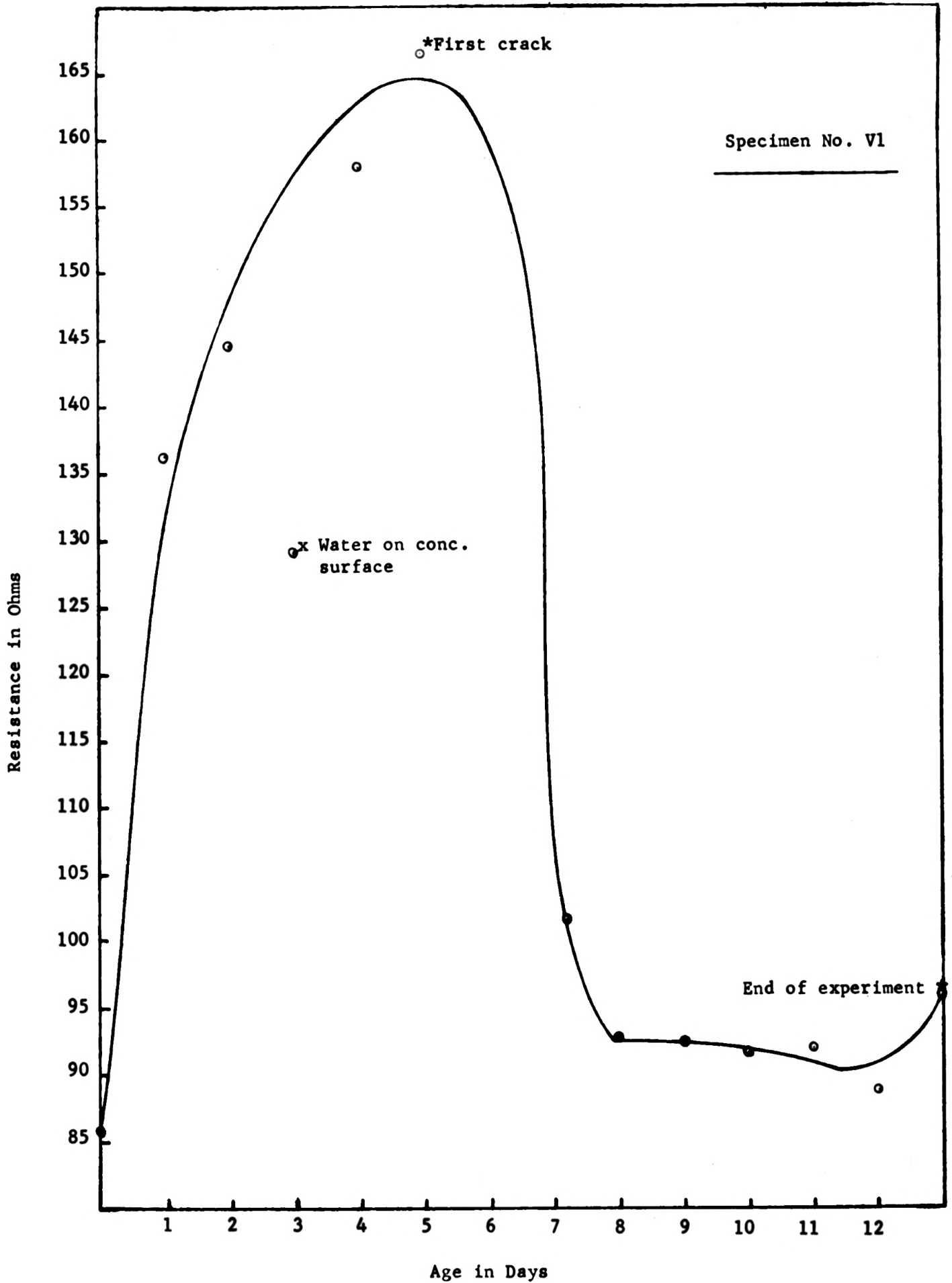
Fig. 1. Variation of Resistance of concrete against age
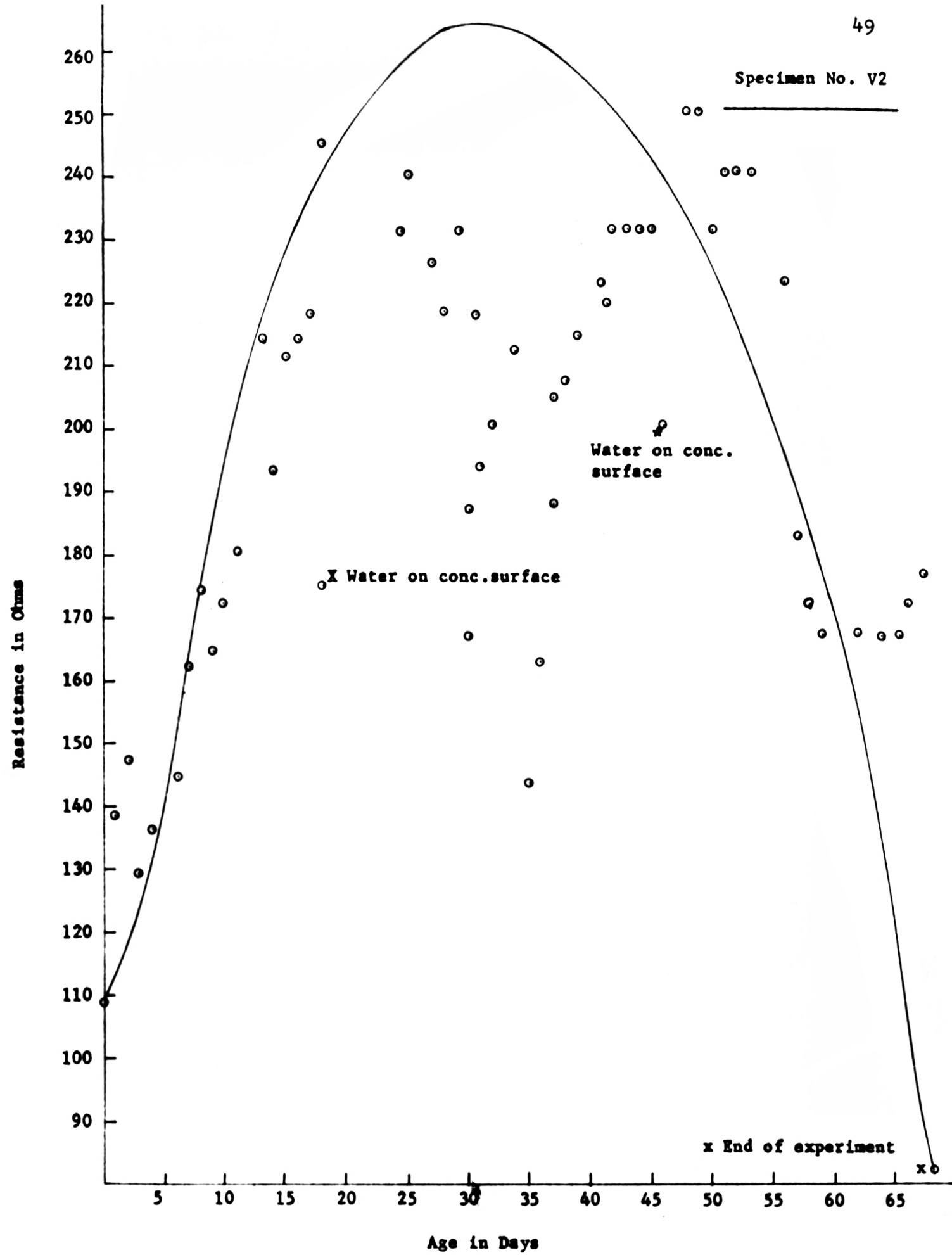
Fig. 2. Variation of Resistance of concrete against age
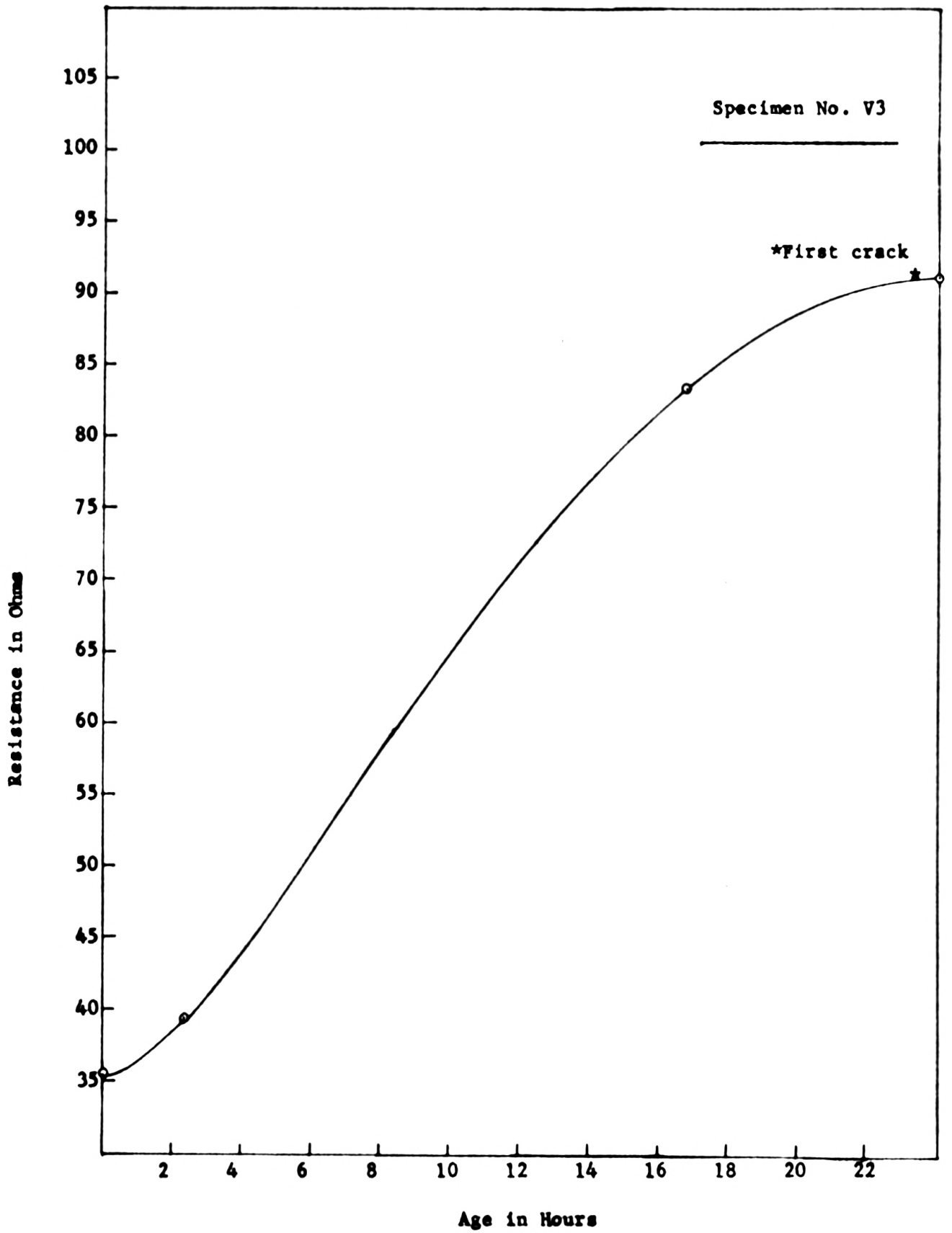
Fig. 3. Variation of Resistance of concrete against age
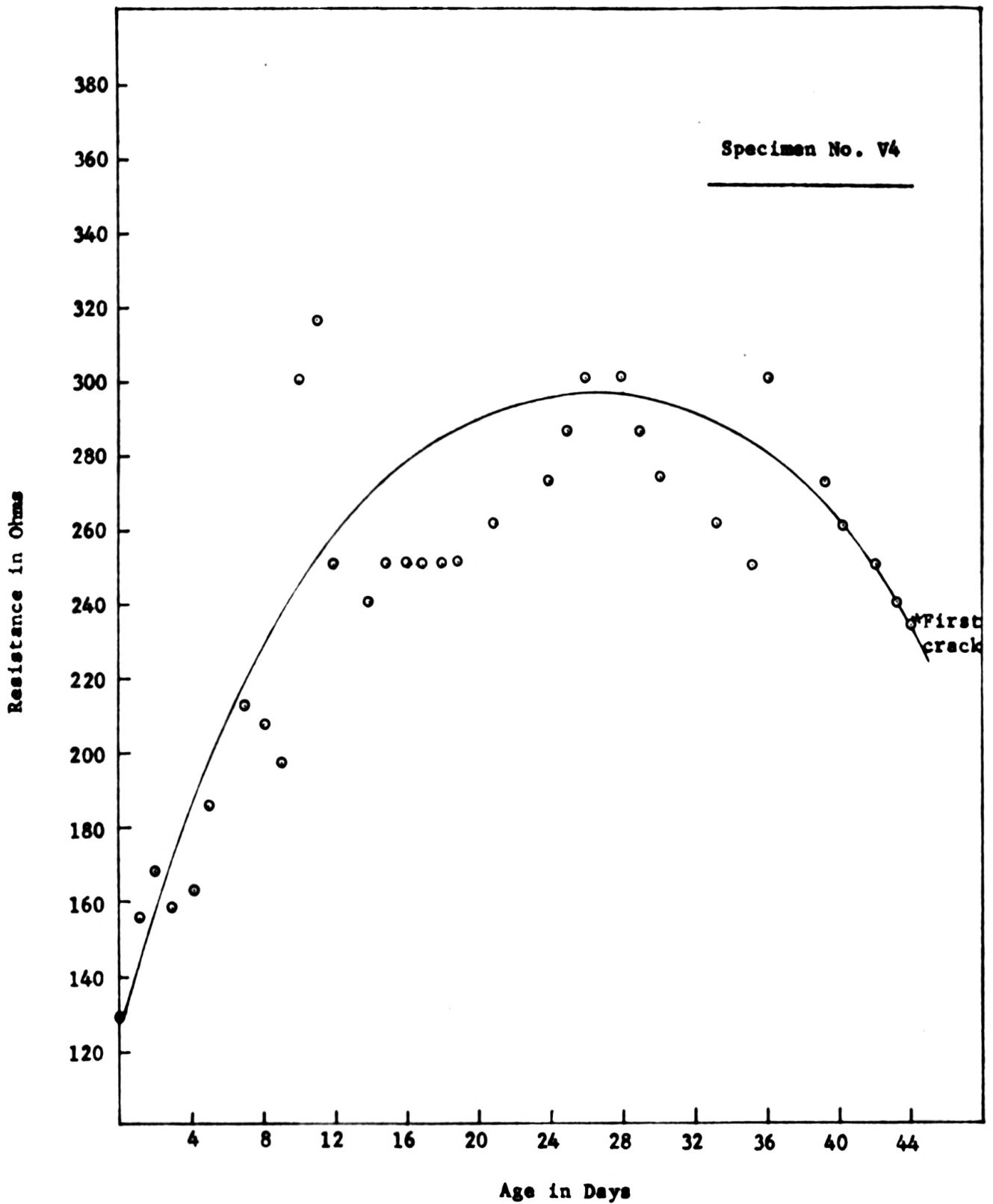
Fig. 4. Variation of Resistance of concrete against age
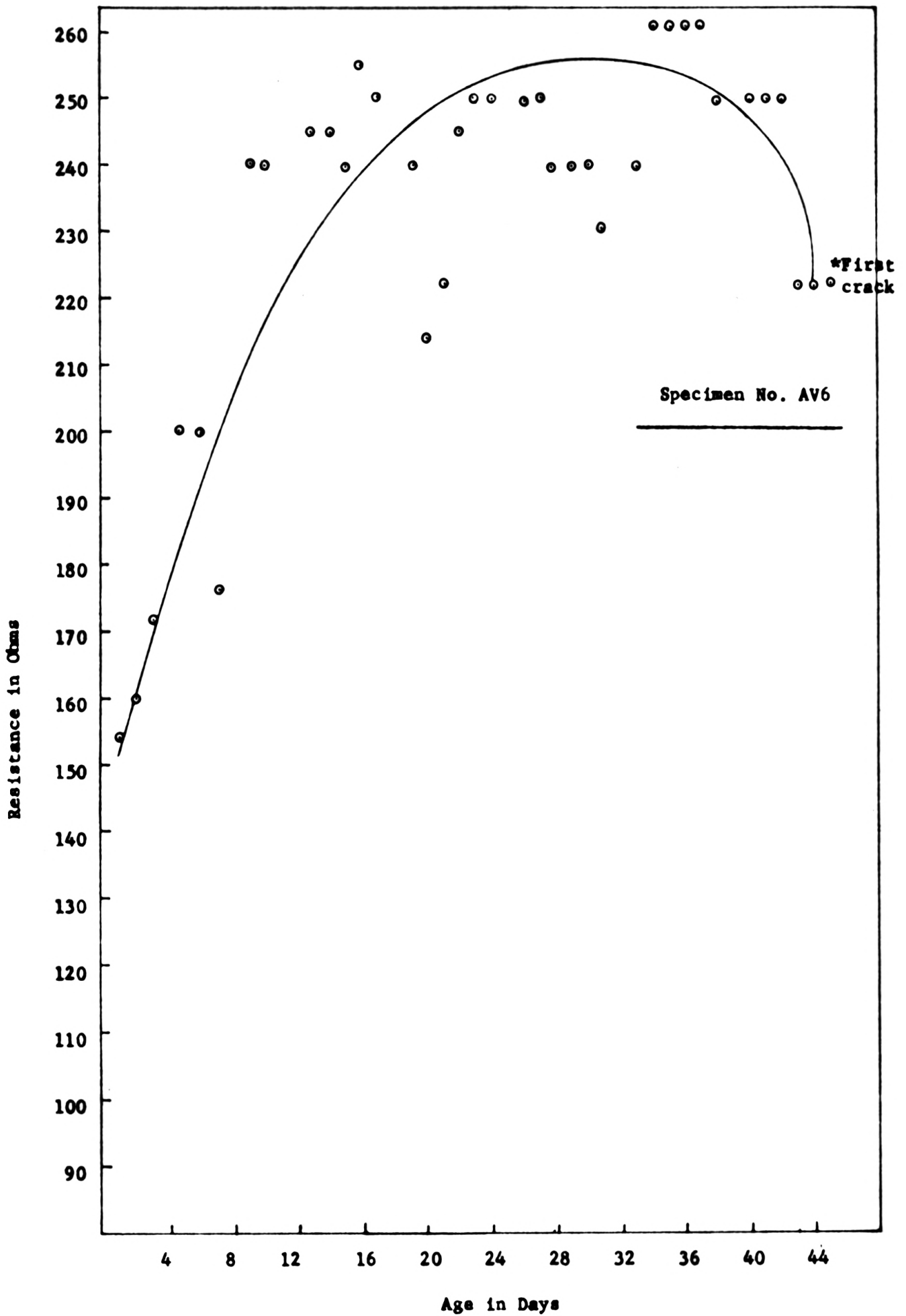
Fig. 5. Variation of Resistance of concrete against age
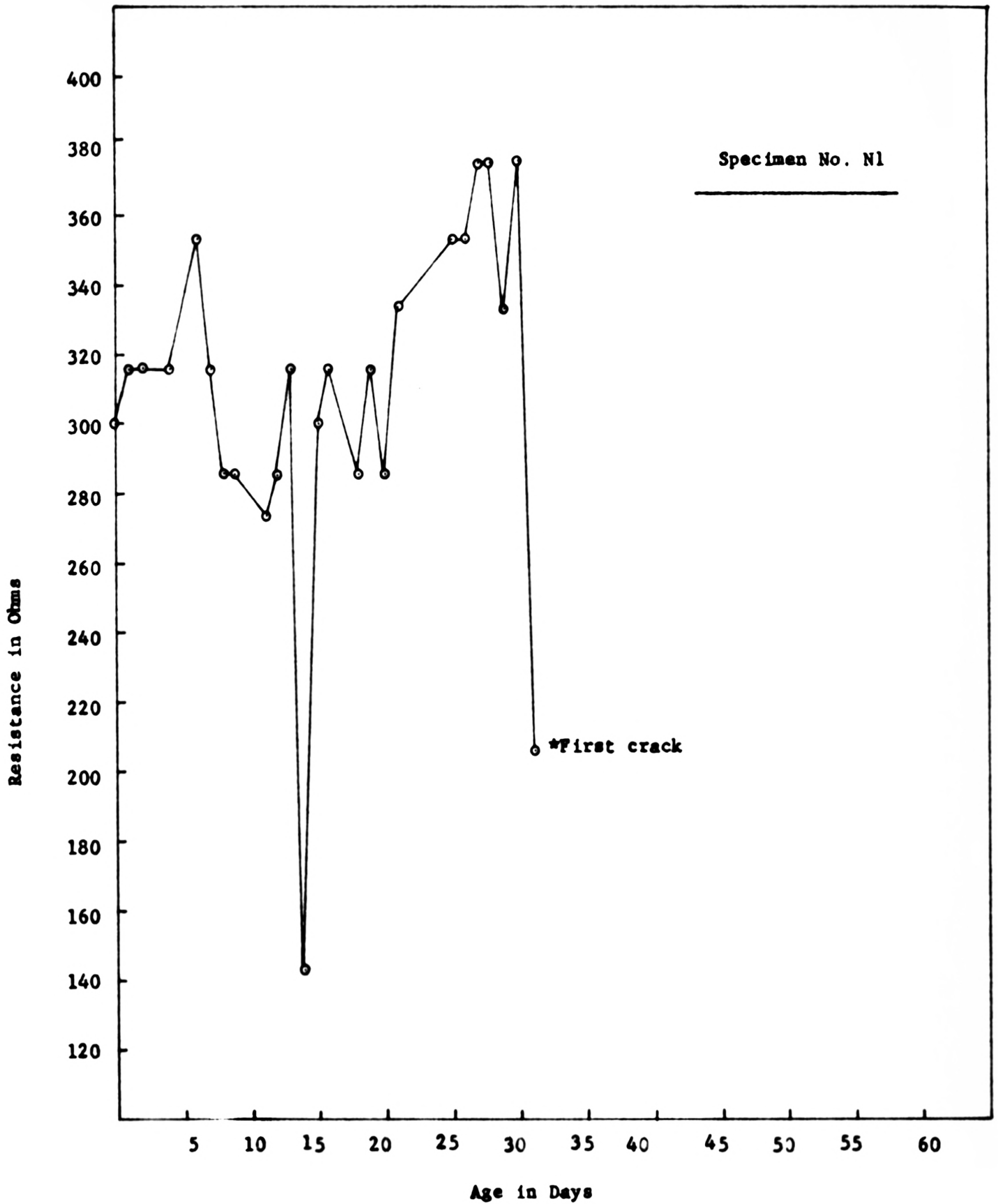
Fig. 6. Variation of Resistance of concrete against age
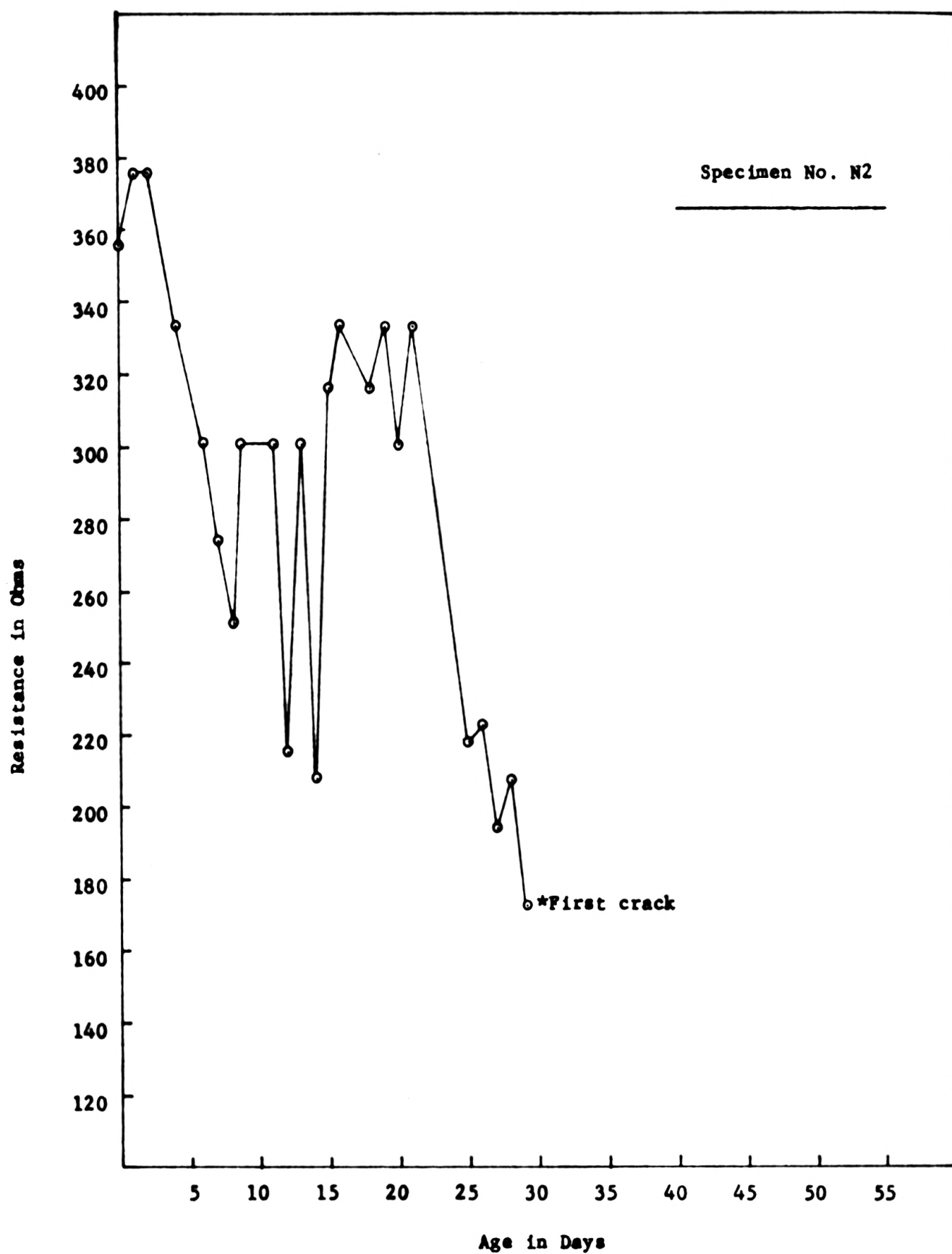
Fig. 7. Variation of Resistance of concrete against age
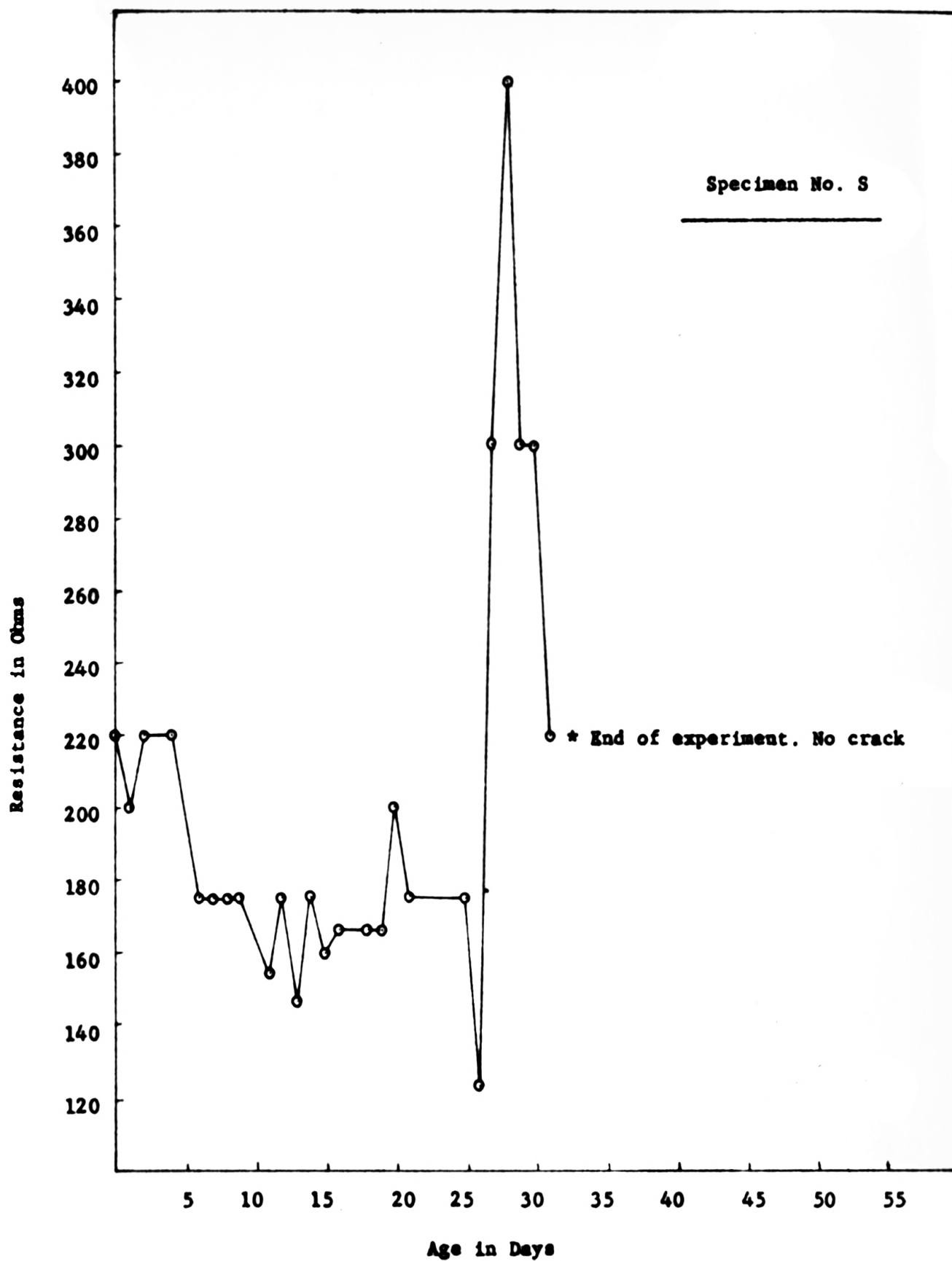
Fig. 8. Variation of Resistance of concrete against age
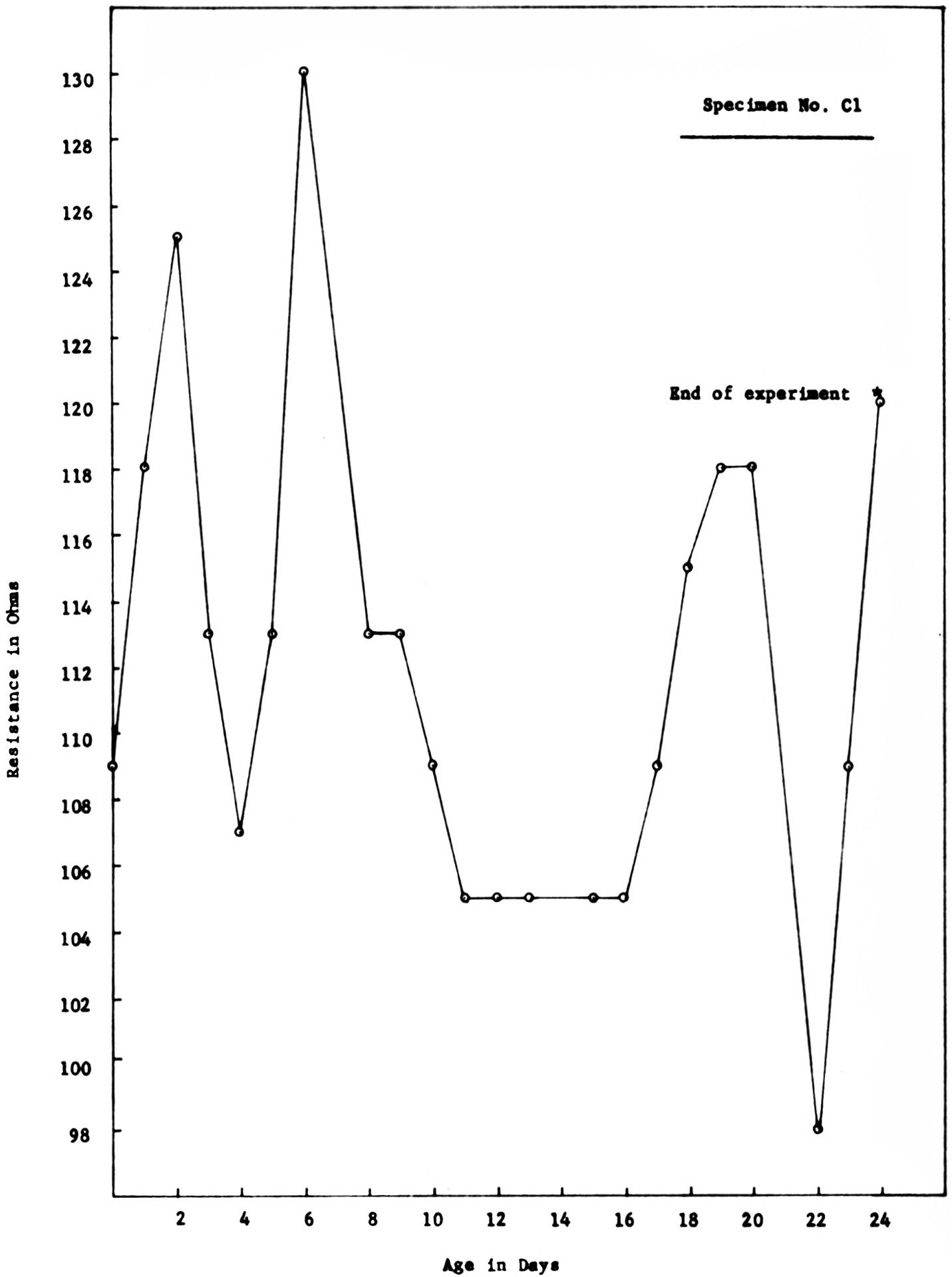
Fig. 9. Variation of Resistance of concrete against age
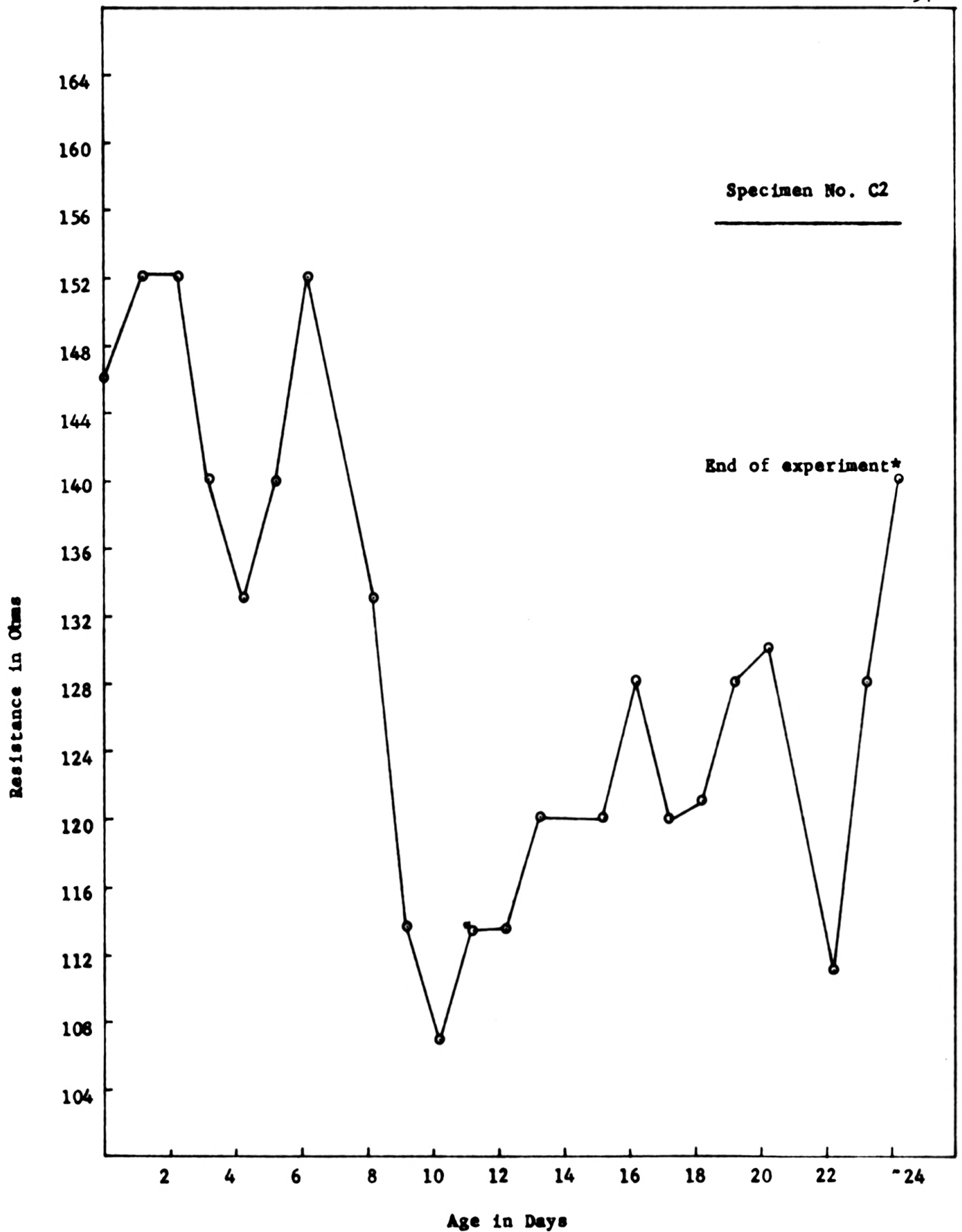
Fig. 10. Variation of Resistance of concrete against age
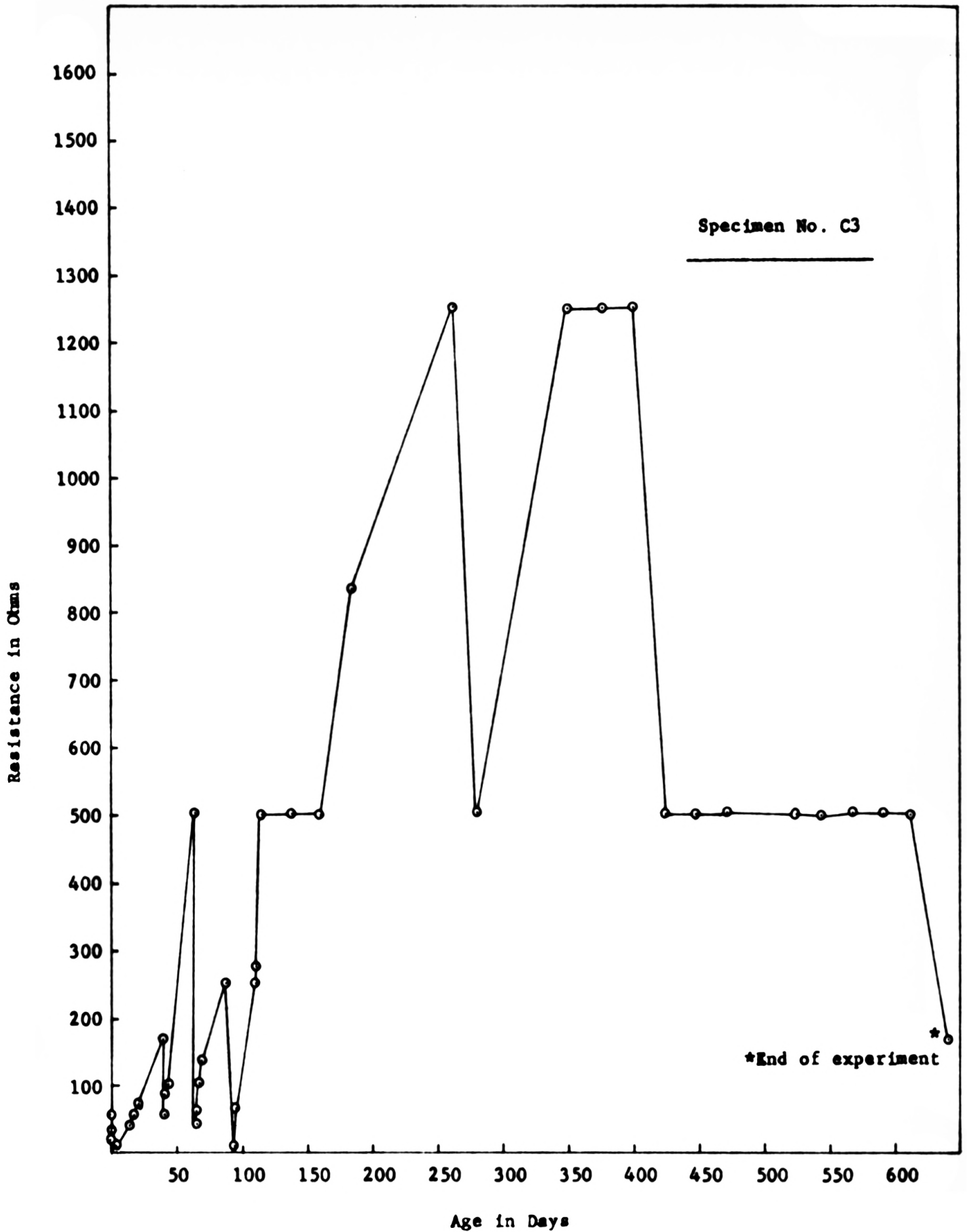
Fig. 11. Variation of Resistance of concrete against age
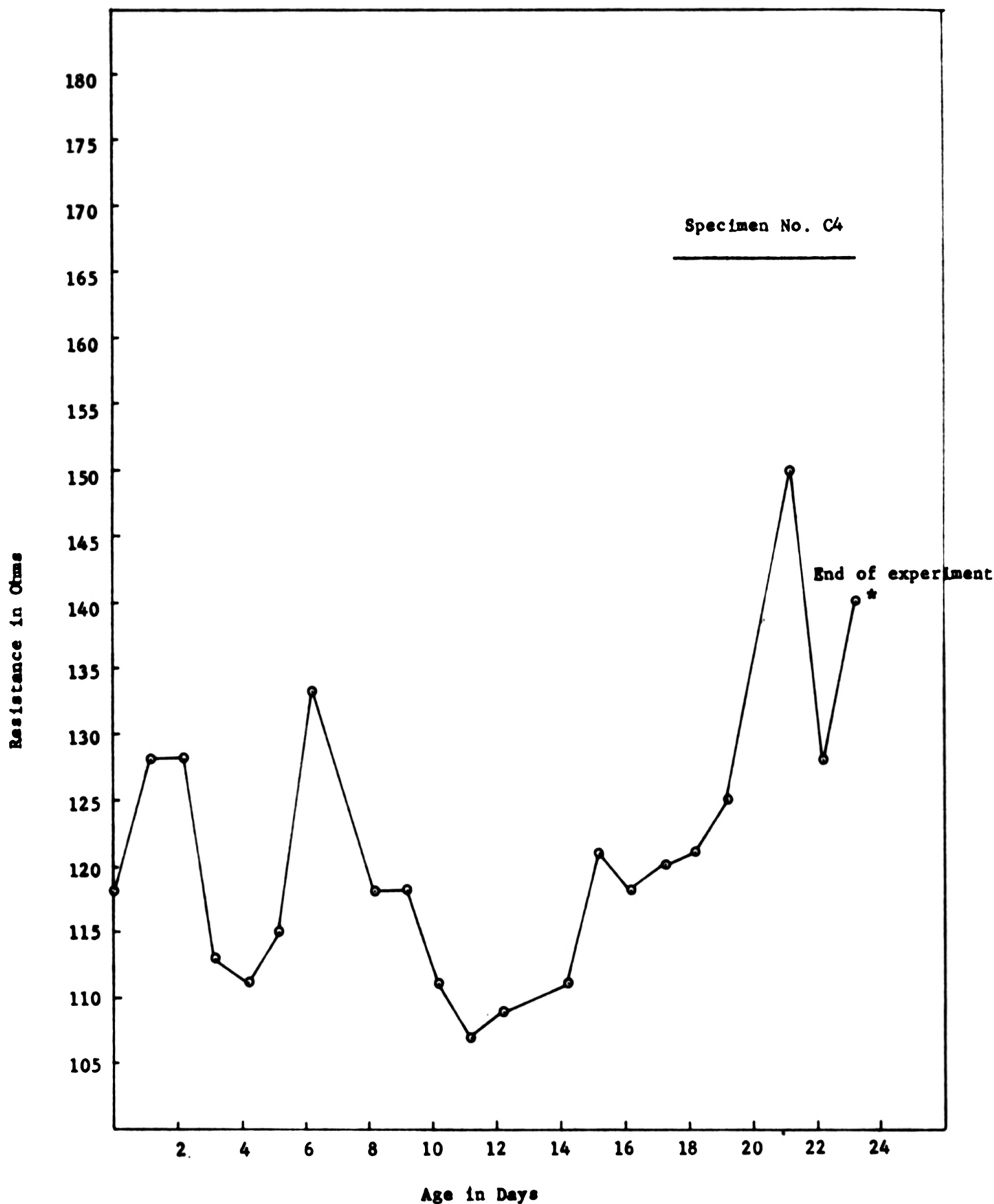
Fig. 12. Variation of Resistance of concrete against age
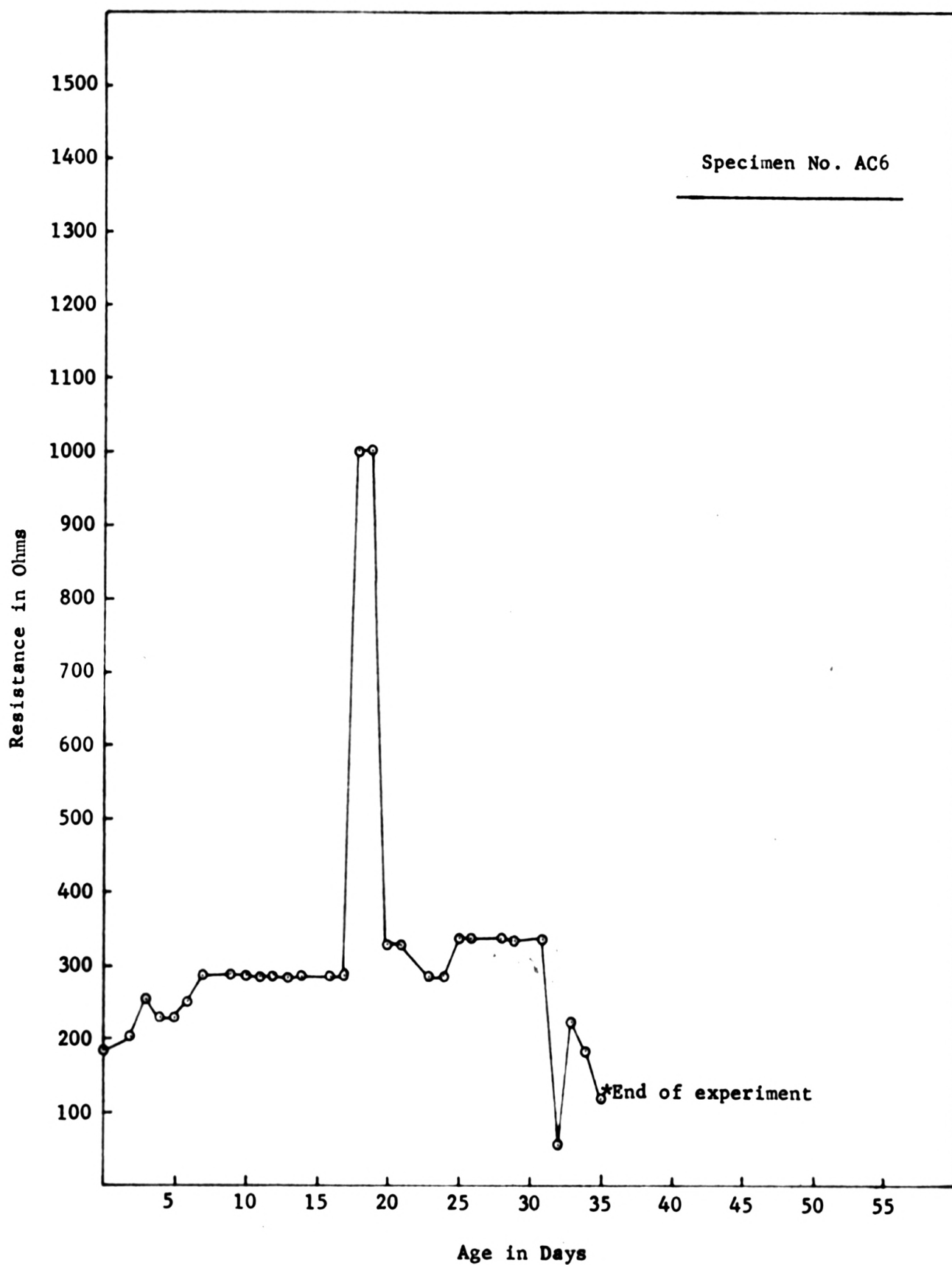
Fig. 13. Variation of Resistance of concrete against age
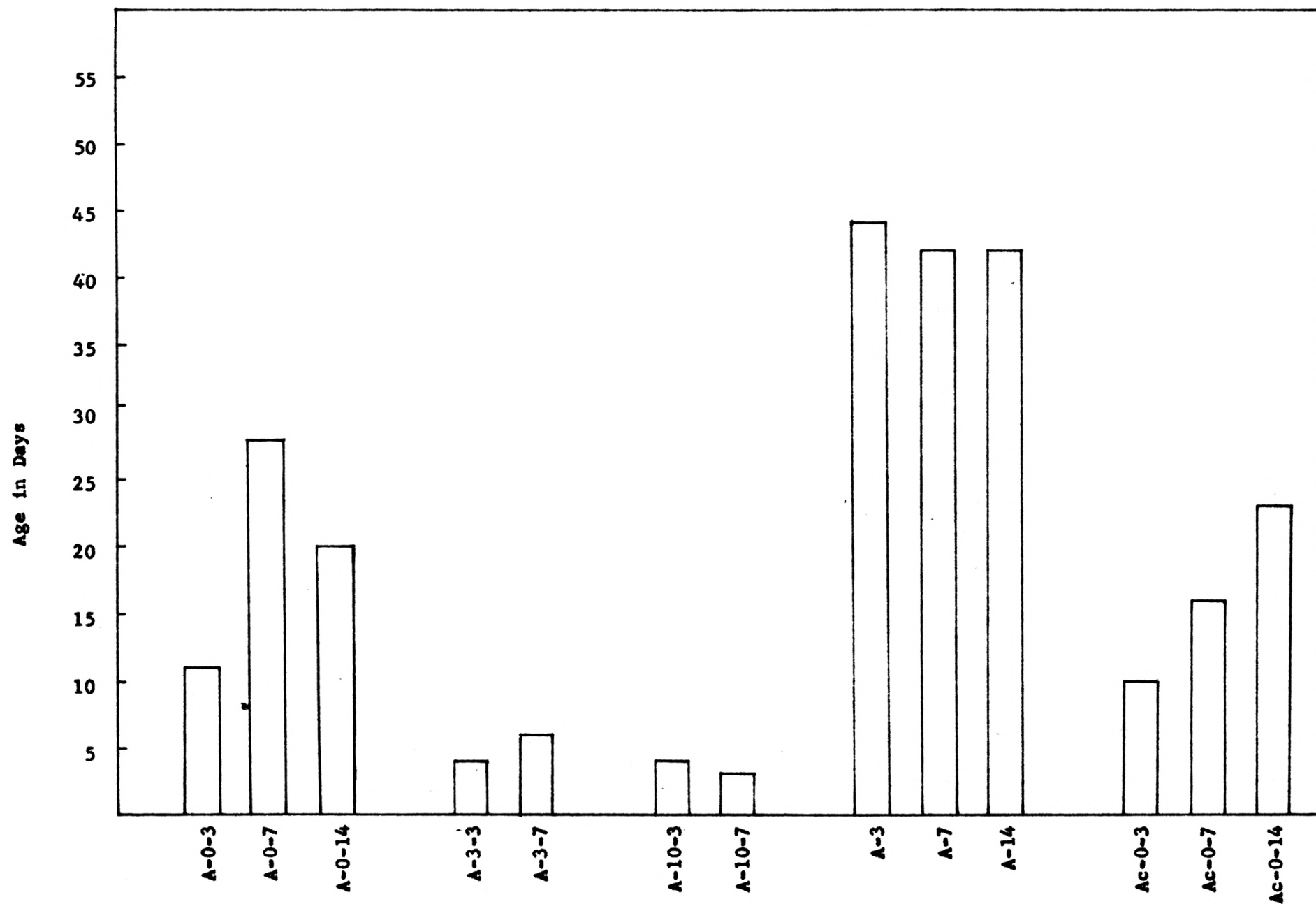
Fig. 14. Comparison of the life of the small specimens
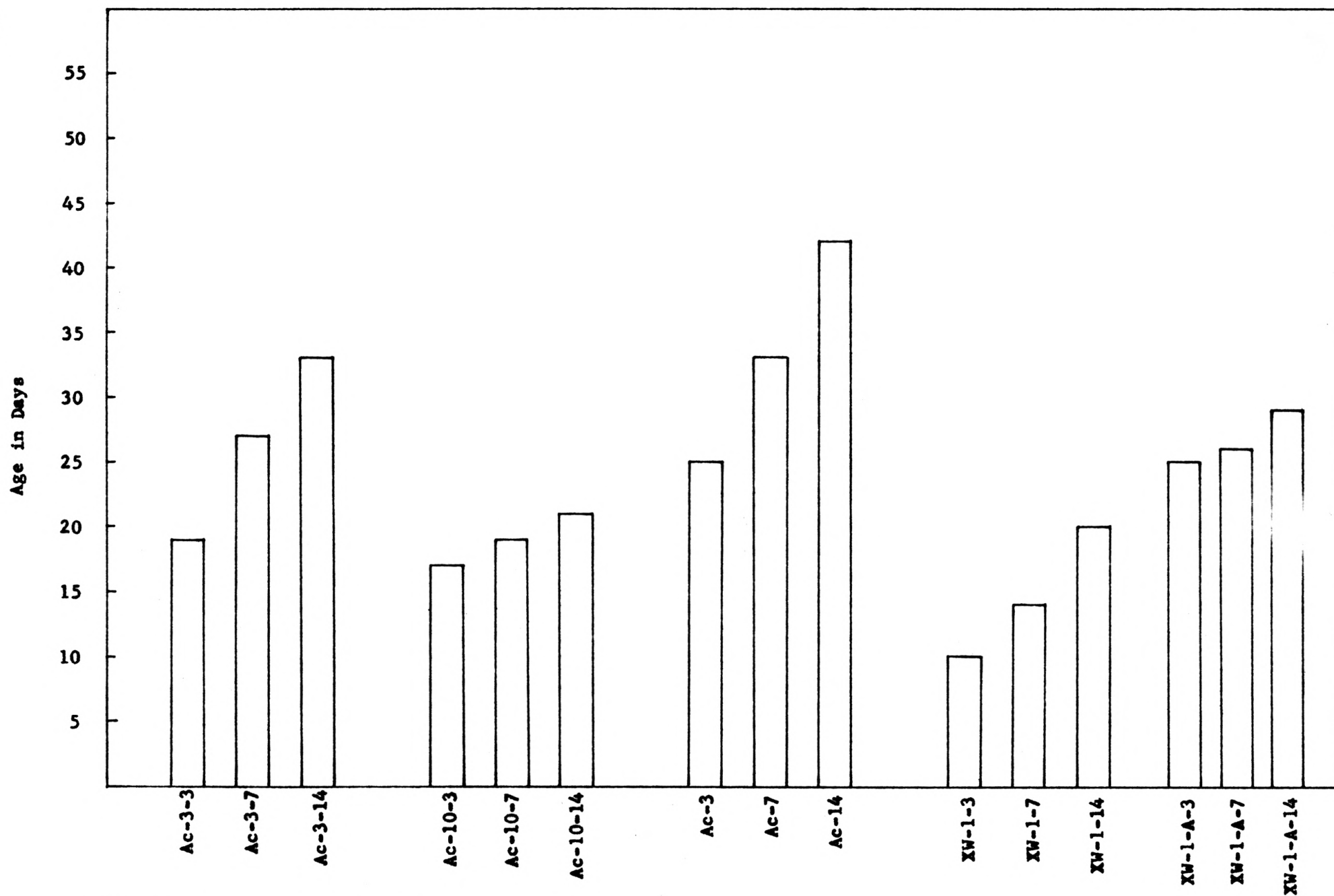
Fig. 15. Comparison of the life of the small specimens

PLATES

EXPLANATION OF PLATE I

Fig. 1. Vertical concrete wall dry dock. The wall was dry at all the time
except when the vessel comes in or goes out. It was subjected to
salt spray mist. The climate of the region is mild. Fresh water
used in mixing this concrete. The wall occasionally filled with
sea water when the vessel enters. The concrete was 5.5 sack co-
ncrete, good quality, and with good aggregates gradation. The
6 bar reinforcement was badly corroded after 15 years. The
reinforcement wascovered by 4" concrete layer.

Fig. 2. Column supporting roof over entrance of club house in the mild
marine exposure. The concrete made with salt free aggregates
with fresh water. The column was exposed to salt spray and mist.
The large crack along the column is due to the corrosion of the
reinforcement. The age of the concrete was twenty years. The
cover of the concrete was 1.5".

PLATE I 66

Fig. 1

Fig. 2

EXPLANATION OF PLATE II

Fig. 1. Piers under heavy fitting out dock. The reinforcement of the
piers were H-columns steel. Steel bars were surrounded the
H-column. No. 14 gage metal form was surrounding the piers
when the concrete poured, then left in its position. The pier
was immersed in see water. The climate was humid with severe
winter weather. No jacket seen in the picture, because it had
been corroded and disappearred with the reinforcement bars.
The age of the concrete was about twenty five years.

Fig. 2. Edge of girder under heavy piers used for construction. Corrosion
of steel causing spoiling of concrete. The age of the concrete
was about twenty years.

PLATE II

Fig. 1

Fig. 2

EXPLANATION OF PLATE III

Low voltage apparatus (6 volts). Three large specimens and twenty four
small specimens were tested each time.

PLATE III
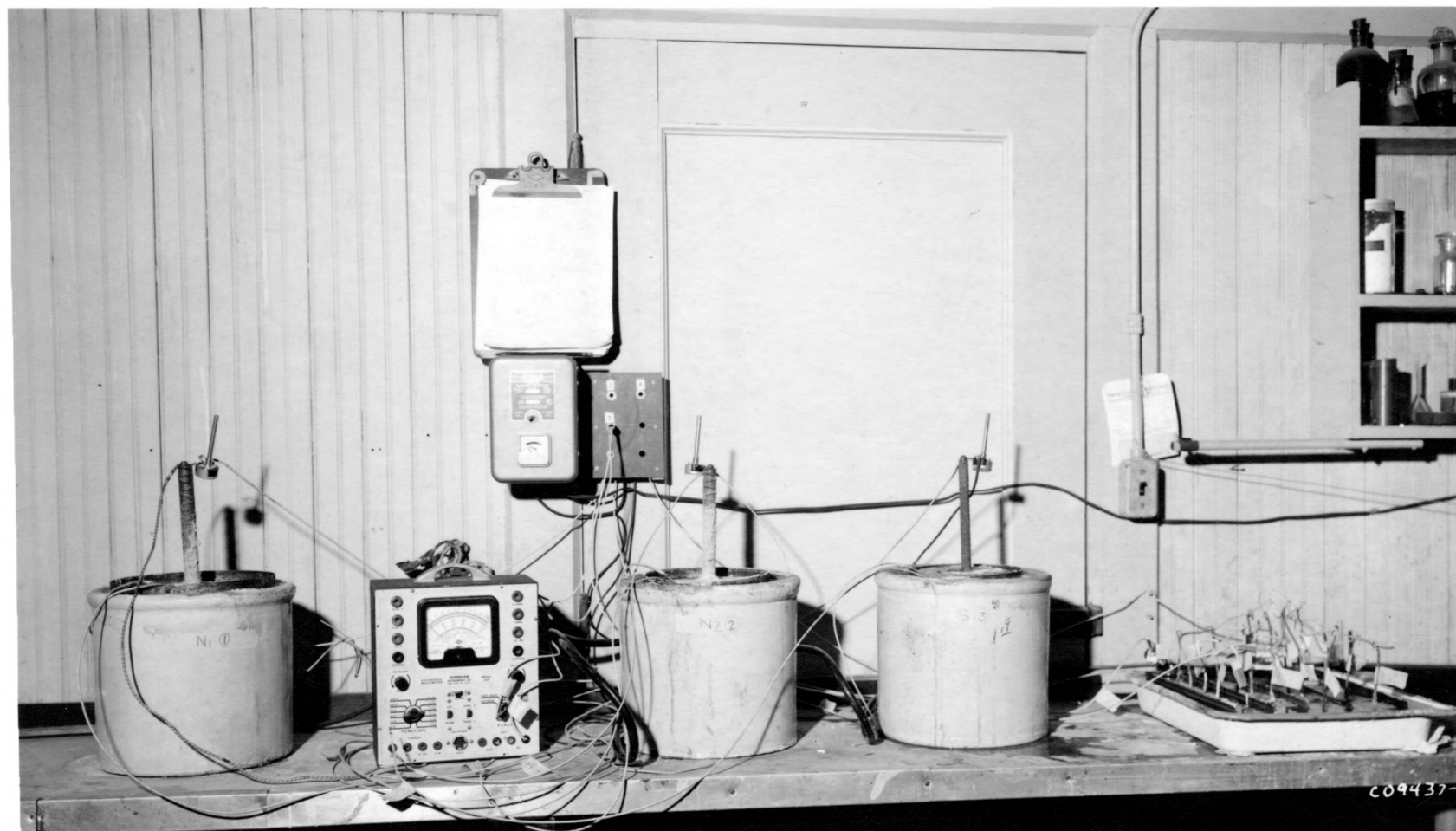
EXPLANATION OF PLATE IV

The corrosion of the steel bar embedded in concrete specimen (V1). The rust moved up to the surface of the specimen after the crack happened.

PLATE IV

EXPLANATION OF PLATE V

The concrete specimen (V1) had been opened after the crack happened. The rust layer appearing on the concrete is due to the corrosion of the steel bar.

C08854-3
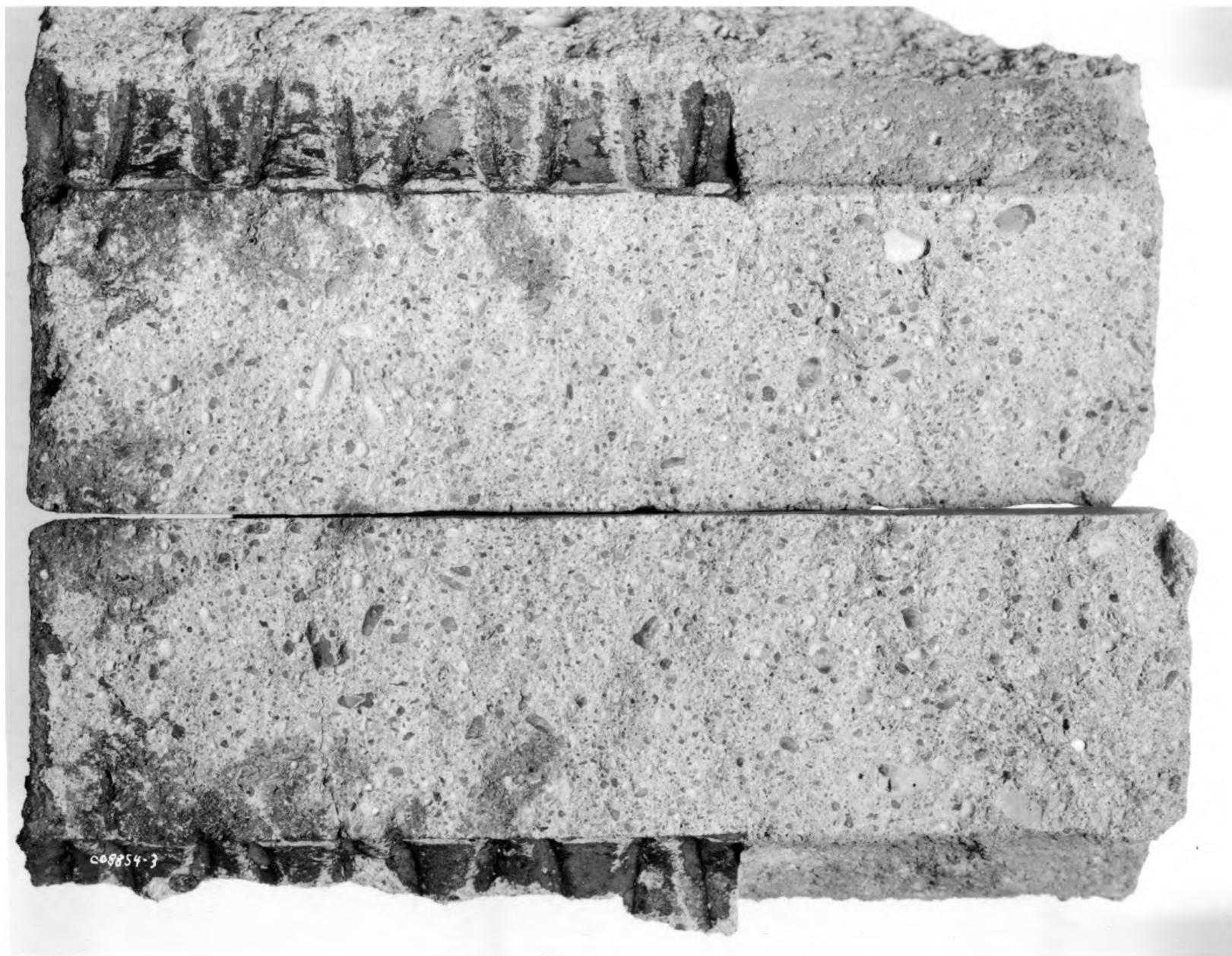
PLATE V

EXPLANATION OF PLATE VI

High votage apparatus (50 volts) with specimen (C3) tested under cathodic

protection.

PLATE VI

EXPLANATION OF PLATE VII

Top view of concrete cylinder tested under cathodic protection of high
voltage current (50 volts). The great amount of salt on the surface of
the concrete, and a layer of rust floating on electrolyte were due to
the corrosion of the iron shell around the specimen.

PLATE VII

CO9437-2
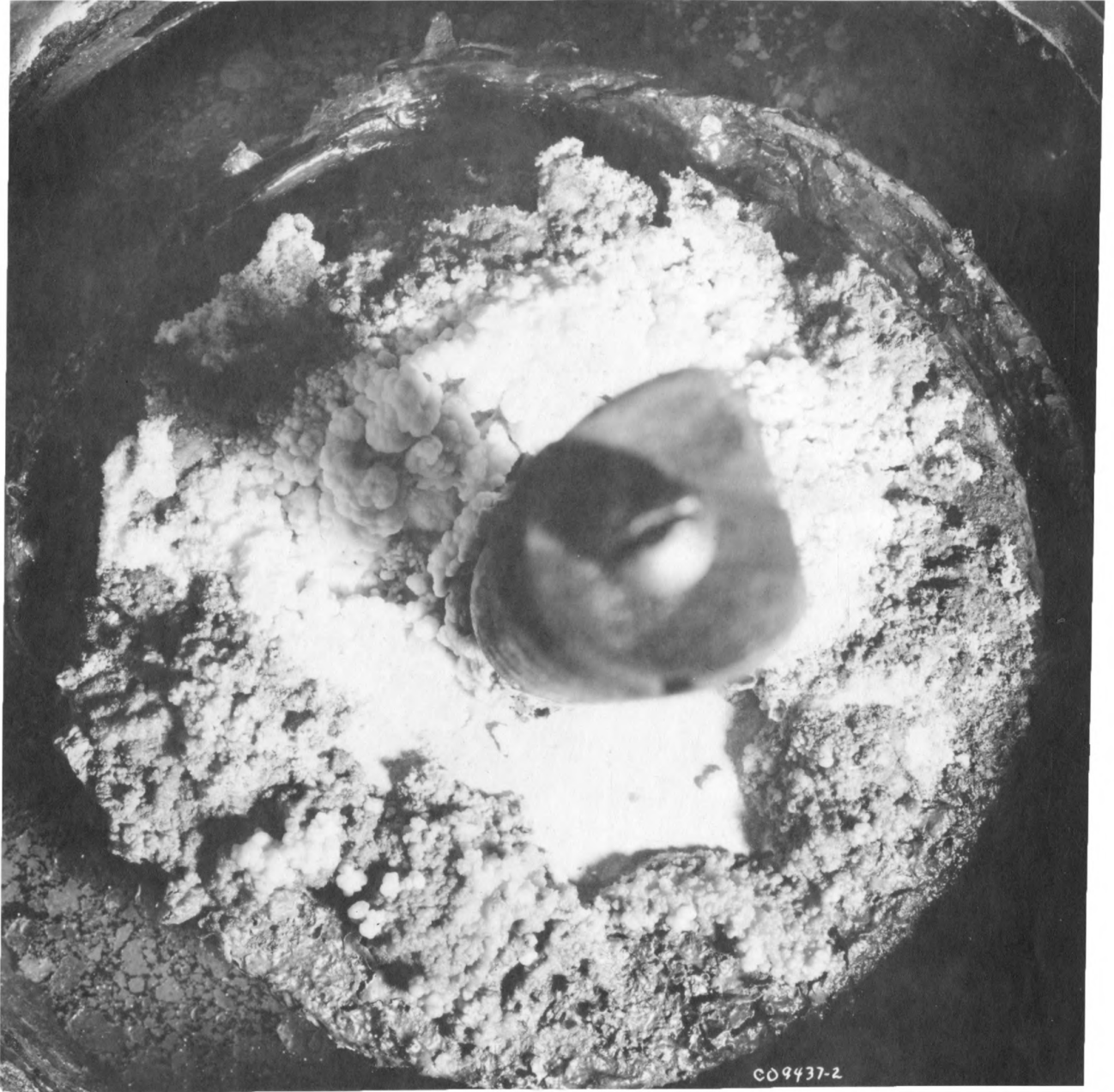
EPLANATION OF PLATE VII I

Diagram showing the connection of high voltage apparatus (50 volts) to the concrete cylinder specimen for anodic effect.

A. Electric supply (110 volts A.C.)

B. Positive wire

C. Negative Wire

D. Transformer

E. 50-volt A.C.

F. Bredge rectifier

G. Voltmeter

H. Rubber jar

I. Iron shell around the concrete cylinder

J. Steel bar embedded in the concrete cylinder

K. Concrete cylinder

L. Electrolyte (10% salt brine)

M. 1" layer of sand

N. Ameter

PLATE VIII
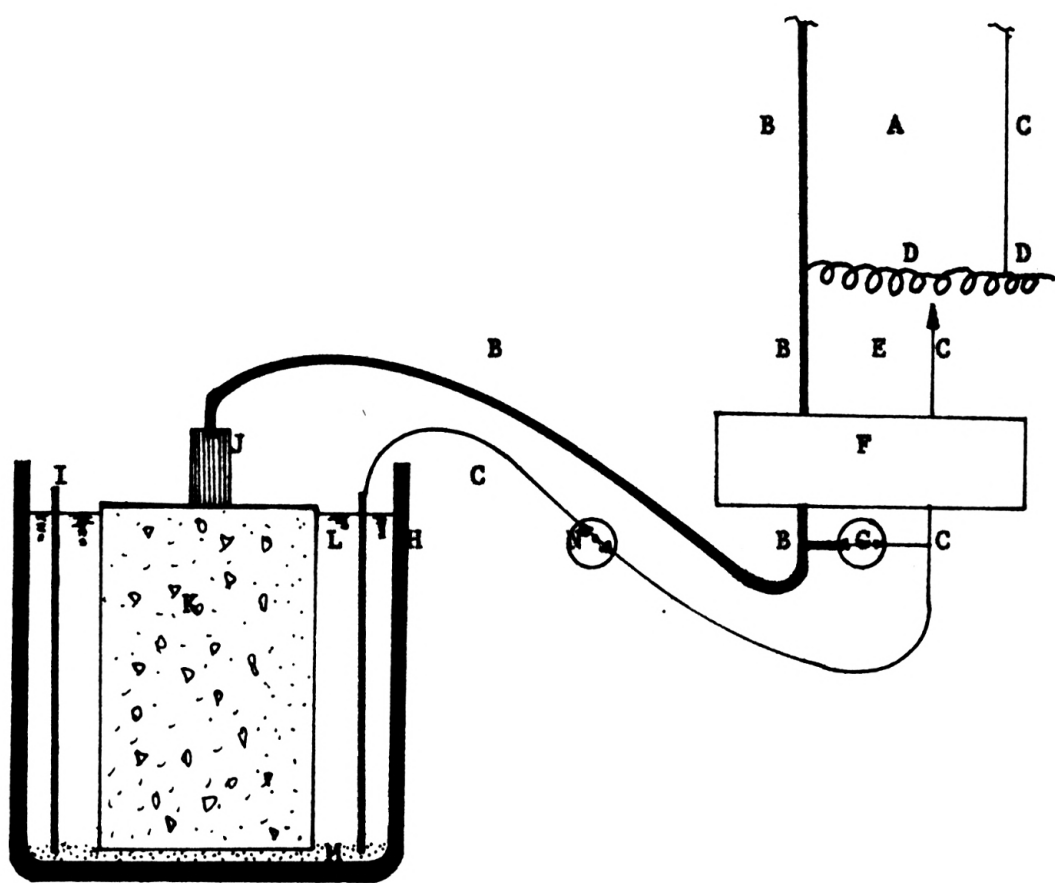
EXPLANATION OF PLATE IX

Diagram shewing the connection of wires in low voltage apparatus (6 volts).

The diagram consists of :

A. Battery charger.

B. Masonite plate.

C. Positive wires.

D. Negative wires.

E. Steel bars embedded in concrete specimens.

F. Iron shells surrounding the specimens.

G. Concrete cylinder specimens.

H. Clay jars.

I. Electrolyte (3% salt brine).

J. Concrete cubes.

K. Voltmeter and an ammeter.

L. Phone jack.

M. 1" layer of sand.

N. Potentiometers.

PLATE IX
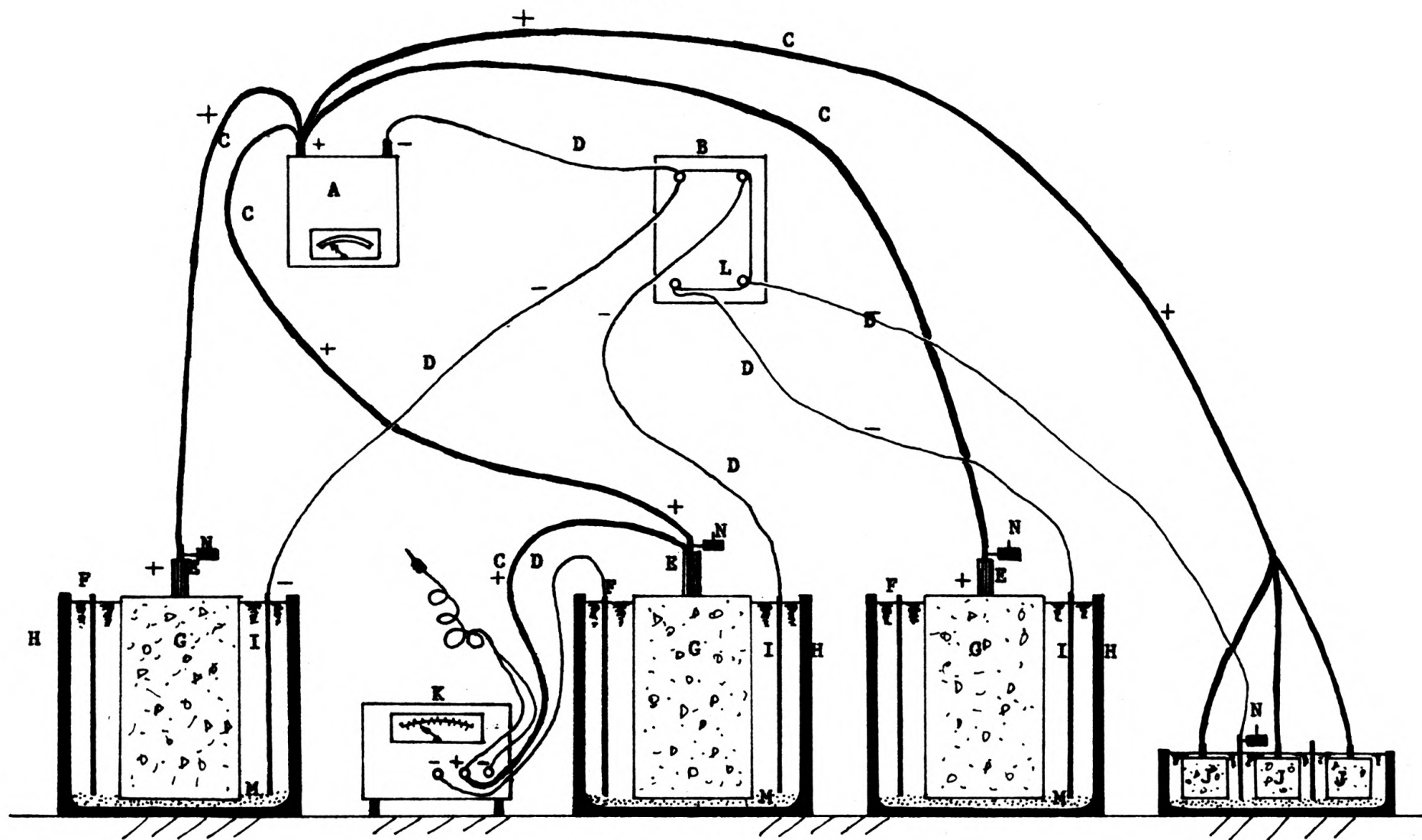
EXPLANATION OF PLATE X

Fig. 1. Diagram showing the large specimen in clay jar.

Fig. 2. Diagram showing the small specimen.

PLATE X
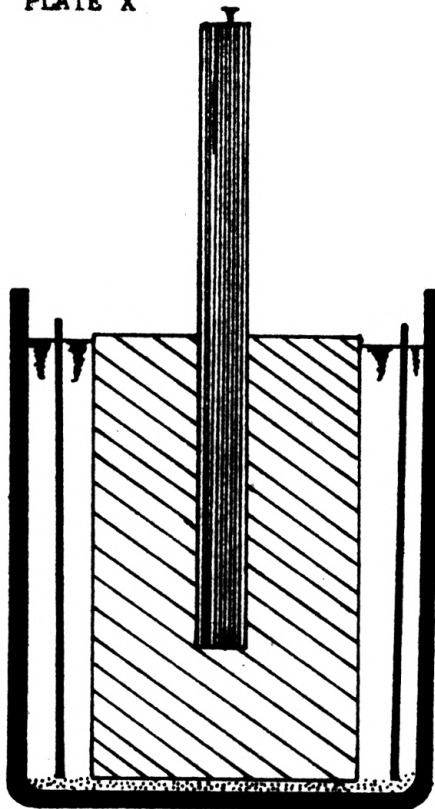
Fig. 1
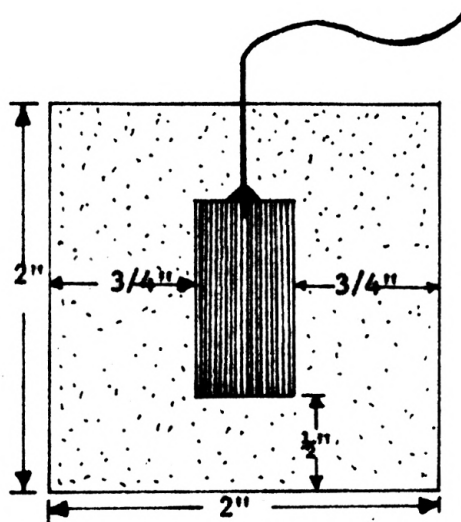
Fig. 2

DISCUSSION OF RESULTS

The quantity of electricity that passes through a specimen does not alone determine the amount of damage that it may do; the rate at which the current flows is also an important factor.

When the large cylinders were tested under the constant voltage direct current (six volts), the anode began to corrode gradually and hydrogen and oxygen gases began to be produced. The iron shell which was acting as cathode stayed clean without any rust or anything happening except that some hydrogen bubbles accumulated on the surface which then tried to escape through the salt brine. The salt brine in this case also remained clean and free from rust. The cracks in the concrete occurred radially first, then more longitudenally, until they spread out all over. After the first crack occurred, others appeared rapidly, while the first crack rapidly enlarged.

When the specimen cracked, the resistance[1] increased to a maximum, and then the resistance dropped. This rise in resistance after cracking would seem to be due to the gases which rapidly filled the crack, due to the rapid electrolytic dissociation of the water which flowed in from the brine.

Cathodic protection tests showed that the steel bar did not corrode when subjected to six-volt direct current and in 50-volt direct current, regardless of the time of the test. The rust

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[1]Resistance as used in this discussion includes resistance due to anodic polarization, cathodic polarization, and the resistance of the concrete.

accumulated on the surface of the shell (anode) after a few min-
utes from the beginning of the test for the six-volts direct
current and faster for the 50-volts direct current.

The rust in cathodic protection tests floated on the salt
brine - electrolyte - and reached the concrete cylinder. A cir-
cle of white salt accumulated at the surface of the concrete,
especially in the very high voltage test.

The resistance of the concrete varied very greatly in the
cathodic protection test. It is thought that the reason for
this is that the accumulation of the gases on the iron bar -
cathode - decreased the resistance of the concrete suddenly, and
then when the gases escape through the concrete outside, the re-
sistance decreased suddenly, and so on. The greater the amount
of gases on the cathode, the less the concrete resistance, and
vice versa. For this reason the resistance of the concrete
changed steadily, and in plotting this resistance versus the
time, connecting the points by straight lines was the best way
to show the variation of the resistance in relation to time.

The temperature of the electrolyte was so high that the
evaporation of the water from the salt brine progressed rapidly
and water was added every two or three days. In the anodic ac-
tion test, when water was added to the salt brine it flowed to
the top surface of the concrete and attached to the steel bar
which caused the resistance of the concrete to drop suddenly to
the minimum; and this water evaporated very fast. When the con-
crete surface became dry again, the resistance returned to the
original, thus these points were not considered and the curve

interpolated between the average of the points.

The cause of the rise of resistance of concrete in the case of anodic action was evidently due to the concentration by the current of calcium hydroxide near the cathode surface resulting from incompletely cured concrete. When the calcium hydroxide comes in contact with CO_2 absorbed by the water from the air, the result will be precipitation of calcium carbonate ($CaCO_3$) within the pores of the concrete near the surface of the specimen; this plugged up the pores and formed a nearly impermeable wall.

In the case of cathodic protection, the rise of resistance, while still greatly in evidence, is much less marked than when the embedded electrode is anode. This might be expected from the fact that CO_2 has very little access to the calcium hydroxide $/Ca(OH)_2/$ at the surface of the embedded electrode, and hence the tendency to produce a dense precipitate of calcium carbonate ($CaCO_3$) would be very slow. In fact, there is good reason to believe that the rise of resistance which takes place at the embedded cathode is due chiefly to the liberation of gases at that point by the electrolysis of water.

The chief factor of raising the resistance of concrete by adding salt to the concrete was the presence of sodium chloride in a solution preventing the precipitation of calcium carbonate at ordinary temperature so that plugging of the pores cannot occur.

In the high voltage (50 v) cathodic test, the temperature

rose very high (85° F.) in the electrolyte, concrete, and iron rod. The current also jumped to maximum, then after a minute it dropped and rose again, and so on. At this time, a clear sound was heard from the apparatus and the ammeter arrow began to shake.

The products of corrosion consist mainly of black or green ferrous hydroxide next to the metal, and reddish-brown ferric hydroxide (rust) which forms the outer layer, with graded mixtures of the two in between.

In coating the small specimens by some protective material, it was very difficult to get a complete coating, even when two layers were used. The current moved through these specimens when tested, which means that the coating material did not do what it was supposed to do even though it was believed that the coating process was well done and the material covered all of the specimens. Some coated specimens acted as if they were uncoated, and the others were slower in cracking. In conclusion, the coating of specimens with waterproofing material is an unsuccessful process and should have no practical application.

The steel bar coated with 0.001 inch or 0.003 inch thick nickel did not prevent the crack of the concrete block. This means the coating did not prevent the corrosion of the steel bar. The life of the concrete in this case was the same as with ordinary steel reinforcement.

CONCLUSION

1. The resistance of the neat cement, when subjected to a small constant voltage (6 volts), increases with time until the first crack occurs in the concrete, then the resistance drops suddenly.

2. A concrete block subjected to a high voltage (50 volts) of direct current, broke in about 22 hours.

3. The neat cement was weakest when the crack appeared in a few days (about five days).

4. The admixture No. 1493 of Puget Sound Pulp & Timber Co. improved the concrete and increased its life about twice the usual life.

5. Increasing the amount of sand in the concrete decreased the concrete resistance and decreased its life, because the greater the amount of sand results in more voids, greater permeability, more moisture, and lower electrical resistance. The increased permeability of the concrete allows a greater amount of moisture and lowers the resistance.

6. The concrete block which had the admixture No. 1493 of the Puget Sound Pulp & Timber Co. maintained a constant resistance for a duration of about five periods of about one week's duration.

7. A constant high voltage direct current (50 volts) passing through the concrete will heat the concrete to considerably above room temperature in one day's time due to the heating of the anode buried in the concrete.

8. For cathodic protection of a concrete block subjected to a high constant direct current voltage (50 volts) for a period of more than a month, when 50 volts cathodic protection was applied, the concrete resistance increased slowly, but no crack appeared.

9. In a neat cement of different curing time /In the water (3 days, 7 days, and 14 days)7 and supplied to a constant voltage direct current (6 volts), the first crack appeared at the same time, i.e., longer curing of the neat cement did not increase the concrete life.

10. When the curing time of an ordinary concrete was increased from three days to seven days, the life span of the concrete was doubled, but when the curing time was increased to 14 days, the concrete life span decreased.

11. Increasing the salt content in the concrete decreased its life.

12. The resistance of concrete in cathodic protection is higher than in the anodic condition.

13. Considerable heating was observed in the 50 volts cathodic test, as evidenced by the fact that considerable water was evaporated each day.

14. There was no waterproofing material found which prevented the corrosion of the reinforcement.

15. The reinforced bar which was coated with a layer of nickel or epoxy resin was not protected from corrosion under the test conditions.

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THE CORROSION OF REINFORCEMENT IN CONCRETE

by

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AN ABSTRACT OF
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The objective of the work was to study the behavior of reinforced concrete when subjected to constant voltage of direct current for low voltage and high voltage in both anodic effect and cathodic effect. The other object was to compare the life of reinforced concrete of different mixing with different reinforcements and different conditions, when the reinforcement corroded.

Corrosion can be defined as the destruction of metal by chemical or electrochemical action. Most of the cracks occurred in the reinforced concrete structure subjected to moisture, due to the corrosion of the reinforcement. Two most important factors, moisture and oxygen, must be present at the same time to make the reinforced bar corrode.

The materials used in this research were: Type I cement, sand, broken stone, a certain type of admixture, and a special kind of waterproofing material. The water cement ratio in this study was six gallons per sack, and this amount differed slightly from one group to another. The most group used of mixing ratio of cement and sand was 1:2.75 by weight.

Two different sizes of specimen were used: (1) Big cylinders of six inches in diameter and eight inches high with steel bars of one inch diameter embedded for five inches in the cylinder; (2) Two inch cubes with plain one-half inch diameter steel bars of one inch length embedded in the middle and connected by an insolated wire to the outside.

Two types of testing were used in the big cylinders after curing for twenty-eight days or fourteen days. The first test

was for anodic effects, making the steel bar as an anode and the iron shell around the cylinder as a cathode. In this case the iron bar corroded badly after different number of days due to the kind of concrete used, while the iron shell which acted as a cathode was not affected. The concrete cylinders cracked after the corrosion of the reinforcement and so many cracks followed the first one that the cylinder could not carry any load or support anything. This cylinder was assumed to be a concrete structure which would be destroyed after the corrosion of the reinforcements, but the individual parts of this destroyed concrete have a very good compression strength which means that the corrosion of the reinforcement will destroy the concrete structure, but will not reduce the strength of the concrete. The other test on the big cylinders was the cathodic effect, or to let the iron bar act as a cathode and the iron shell as an anode. In this case the iron shell corroded badly but nothing happened to the iron bar and no cracks appeared in the concrete for a long period of time under this test. Two constant voltages of direct current were used in these tests for the big cylinders. The first was six volts direct current supplied from a battery charger and most of the cylinders were put under this test, while only a few of them were put under a very high voltage of fifty volts direct current supplied from the natural electric source of the room passed through auto transformer to change the 110 volts alternate current to fifty volts alternate current and then through a rectifier to change the alternate current to direct current.

The electrolyte for the low voltage test was three per cent salt brine, while in the high voltage test ten per cent salt brine was used.

From these tests it was found that the resistance of the concrete increases due to its age in both anodic effect and cathodic effect, but in the cathodic effect it changes faster than in the anodic effect.

The life of the concrete under the anodic effect test varies with different mixing ratios and it increases with the decreased amount of sand, while it decreases with an increased amount of salt.

The small cubes specimens were tested under six voltage direct current only to find the life of the concrete of different mixing ratios and different admixtures. Also some of these cubes had been coated to study the life of the concrete in this case.

These tests showed that there was no use in coating the concrete for several reasons: one, it is very difficult to make a complete and perfect coating; and two, there are no perfect waterproofing materials to prevent the corrosion of the reinforcement or stop the flow of the current from the embedded bar to the outside of the concrete to the iron plate surrounding it.