DIVISION OF STRUCTURES AND ENGINEERING SERVICES

TRANSPORTATION LABORATORY

RESEARCH REPORT

Corrosion Evaluation Of Iron Blast Furnace Slag

FINAL REPORT

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Corrosion tests indicated that slag aggregate combined with water is about as corrosive to steel as a moderately corrosive soil. Leach water from slag aggregate can become highly corrosive as the probable result of the natural acidification of the dissolved sulfur compounds.

Exposed to saturated salt solution, slag aggregate in concrete does not result in an earlier initiation of corrosion as compared to a natural aggregate. However, the area of corrosion of steel in slag concrete is greater while the pitting is greater in natural aggregate concrete.

Because of the high content of soluble sulfur compounds, it is possible that leach water could convert to an acid and attack concrete. Also, the high sulfur content leach water may attack portland cement concrete if it does not have a reasonable level of sulfate attack resistance.

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STATE OF CALIFORNIA
DEPARTMENT OF TRANSPORTATION
DIVISION OF STRUCTURES & ENGINEERING SERVICES
OFFICE OF TRANSPORTATION LABORATORY

July 1976

TL No. 645231

Mr. C. E. Forbes
Chief Engineer

Dear Sir:

I have approved and now submit for your information this final research project report titled:

CORROSION EVALUATION OF IRON BLAST FURNACE SLAG

Study made by . . . . . Roadbed and Concrete Branch

Under the Supervision of . . . . . D. L. Spellman

Principal Investigator . . . . . R. F. Stratfull

Report Prepared by . . . . . R. F. Stratfull

Very truly yours,

George A. Hill

GEORGE A. HILL
Chief, Office of Transportation Laboratory

Attachment
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ACKNOWLEDGEMENTS

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INTRODUCTION

On October 22, 1970, this project was initiated to study the effect of blast furnace on the corrosion behavior of steel when the aggregate was used as a highway construction material.

This effort was given impetus by the possible use of what was considered a waste material for highway construction

The benefit in using the material was thought to not only be to the construction program, but also to inhibit the growth of the waste slag pile in Fontana, California.

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SUMMARY AND CONCLUSIONS

Slag Aggregate

When slag aggregate contains sufficient water, it is moderately corrosive to steel. Steel in direct contact with slag should be protected from accelerated corrosion.

Some slag aggregates contain a considerable quantity of water-soluble sulfur compound which may, under certain conditions, attack portland cement concrete.

Water that drains from slag aggregate can chemically react and produce a highly corrosive and odorous acid solution.

Slag Aggregate Concrete

There does not seem to be a critical corrosion problem using steel reinforcing in slag concrete when the exposure is to tap water. In salt water, the time to the initiation of corrosion is about the same as for natural aggregate concrete. However, it appears that because of the greater porosity of a 5-sack slag aggregate concrete versus a natural aggregate concrete, the time to corrosion-caused concrete cracking may be longer in the slag aggregate concrete. For the 7-sack concrete, the difference in time to cracking does not appear to be significant.

Measurements of the corrosion of steel indicated that for the natural aggregate concrete there was greater pitting but for the slag aggregate concrete the area of corrosion was greater.

It should be pointed out that slag aggregate contains many compounds of sulfur and under the conditions of active corrosion, it may result in stress corrosion of prestressing steel.

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Under the conditions of continual water contact or even fog or spray, slag aggregate concrete can discolor in the ranges of a dark blue green to a more or less black when the concrete dries.

Chemical Composition of Slag

Blast furnace slag was obtained from 20 sources outside of California as well as 31 samples from the Fontana Plant. These samples were chemically analyzed for total sulfur compounds, sulfate and chloride. The results are shown on Figure 1.

The test results indicated that Fontana slag was somewhat higher in sulfur compounds (10.1 vs 8.4 lbs/yd^3) than other United States sources. This difference in sulfur compounds is not considered significant.

The Fontana slag used to make concrete was originally found to contribute a non-corrosion causing chloride level of about 0.1 versus 0.06 pounds per cubic yard of concrete for other sources. Further investigation revealed that the source of the chloride was the recirculated cooling water that is used initially cool and break the slag. This chloride level was reduced by not recirculating the cooling water.

Concrete Test Specimens and Test Methods

Test specimens were cast using concrete containing 5 and 7 sacks of cement per cu yd and Fair Oaks natural aggregate and Fontana blast furnace slag. Each of 40 specimens cast of each aggregate type (for a total of 80) contained a one-half inch diameter reinforcing bar with a concrete cover of one inch. One-half of the concrete specimens were steam-plus water cured for a total of 28 days and the other half were water cured for a total of 28 days. (The steam cure period was approximately 16 hrs at 150°F.)

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A total of 20 specimens were partially immersed in plain tap water and the other 20 were partially immersed in saturated sodium chloride salt water to a depth of 3-1/2 inches. One half of the concrete specimens in each test environment was steam cured, the other half water cured. There were a total of 5 replicate test specimens for each concrete corrosion test.

The maximum aggregate size was 3/4" and the slump varied between 2" and 3". The entrapped air content averaged about 1.5%. Fair Oaks sand was used as fine aggregate in the slag mixes.

The 28 day volumetric absorption of 6" x 6" cylinders averaged 13.8% for Fair Oaks aggregate and 15.3% for the concrete made with Fontana slag aggregate.

Corrosion Testing - Half Cell Potential in Salt Water

Half cell potentials of the steel were measured thrice weekly using a calomel half cell. The results of the measurements are shown on Figures 2 and 3. As shown by these figures, there is no significant or meaningful difference in the half cell potential of the steel in either aggregate type of concrete both prior to or after corrosion began.

As shown on Figure 4, "Days to Active Potential", for the 5-sack mix, the time to active potential, or the beginning of corrosion, was slightly longer for the slag aggregate while the reverse was true in the 7-sack concrete. Considering the small differences in these test results, it is likely that slag does not significantly affect the penetration rate of chloride into the concrete.

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Corrosion Testing - Concrete Cracking

As shown on Figure 5, "Days to Cracking", it appears that corrosion-caused concrete cracking in 5-sack concrete may take longer to occur for slag aggregate. The reason may be that the cement paste has a relatively high water-cement ratio and the slag is more absorptive, resulting in some absorption of corrosion products. This would postpone the development of bursting forces.

For the 7-sack concrete, it does not appear that there is a significant difference in time to cracking when using slag aggregate. The reason may be that the water-cement ratio of the paste is low which resulted in minimal corrosion product absorption and, therefore, bursting forces were created early in the corrosion process.

The testing was not completed on the seven sack moist cure concrete because of time limitations. Figure 5 shows the number of samples that were observed to be cracked at the termination of the test. The letter "N" on Figure 5 denotes the number of cracked concrete blocks. A total of 5 concrete blocks were used for each concrete variable.

Corrosion Testing - Corrosion of Steel

Figure 6, "Corrosion Rate of Reinforced Concrete", was determined by removing the steel, cleaning and measuring the depth of pitting with a micrometer. The area of corrosion was determined by first coating the clean bar with ink and rolling it across a clean piece of paper. The corroded areas did not leave a colored residue on the paper. The "corrosion areas" were then planimetered.

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As shown on Figure 6, pitting of the steel in the slag concrete was less, but the area of corrosion was significantly greater than found in natural aggregate concrete.

The test results indicate that once corrosion begins in slag aggregate concrete, it will spread more rapidly.

Corrosion Testing - Half Cell Potential in Tapwater

Specimens containing five and seven sack concrete mixes were partially immersed in tapwater and the half cell potential was periodically measured with a saturated calomel half cell. The results are shown on Figure 7, "Fair Oaks Specimens in Tapwater" and Figure 8, "Slag Specimens in Tapwater". As shown by the data on these two figures, the half cell potential of the steel in both aggregates behaves similarily. No corrosion was observed on the steel removed from either type of concrete.

Concrete Exposure to Water

Fou-concrete beams containing slag-aggregate were tested and then placed in the concrete fog curing room for a period of about one year.

Within the one year period the surface of the concrete was stained with an intense blue-green color. After removal of the concrete beams from the continuously wet fog room the concrete surface turned black.

Apparently, if the slag aggregate concrete is exposed to continuous or even intermittent moisture, chemicals in the aggregate can migrate or form other compounds and result in surface staining.

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Corrosion Testing - Solution of Water and Slag

Slag and distilled water were mixed in 40 containers and the pH or hydrogen-ion concentration was measured for a period of 115 days. As shown on Figure 9, "Solution of Water and Slag - Slag Leachwater After Removal from Slag", the pH averaged about 10.0 and ranged between about 8.5 and 12.0. Then steel corrosion probes (corrosometer) were inserted for a period of 17 days for measurement of corrosion rate. Thereafter, the corrosion probes as well as the aggregate were removed and the pH of the leachwater was periodically measured.

As shown in Figure 9, the pH of the aggregate free leachwater dropped from an average of about 8.0 to approximately 4.8, with a minimum of about 2.7.

Apparently, without the presence of the lime in the aggregate, oxygen may combine with the sulfur compounds and result in a highly corrosive acid condition.

As shown on Figure 10, "pH After Change of Water with Aggregate", the presence of aggregate seems to maintain the average pH at about 10 with a range between about 8.0 and 12.0.

Corrosometer probes were placed in distilled water and slag solution as well as a slag leachwater (without the aggregate and after standing for 38 days) to measure the corrosion rate of the steel. As shown on Figure 11, "Corrosion Rate of Steel (mpy)" for the time of the testing, the corrosion rate of the steel was not significantly different in water that is either free of or contains the slag aggregate. Other tests were performed, and it was found that the corrosion rate of steel was about equivalent in natural aggregate water, distilled water, and slag water.

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It should be noted that all corrosion rates measured would be considered to be corrosive as the measured value was similar to that expected in moderately corrosive soils.

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RESEARCH IMPLEMENTATION

This research has been implemented and has resulted in appropriate additions and changes in our Standard Specifications.

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FIGURES

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CHEMICAL COMPOSITION OF SLAG

SPECIMENS	CHEMICAL ANALYSIS	P.P.M.			LBS/C.Y. of CONCRETE		
		MAX	AVG	MIN	MAX	AVG	MIN
FONTANA SLAG N=31	Sulphur	4600	2819	675	16.6	10.1	2.4
	Sulphate	2835	1499	400	10.2	5.4	1.4
	Chlorides	150	39	0	0.5	0.1	0
OTHER SLAGS N=20	Sulphur	3540	2347	450	12.7	8.4	1.6
	Sulphate	2965	1558	0	10.7	5.6	0
	Chlorides	80	16	0	0.3	0.06	0

FIGURE 1

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FIGURE 2

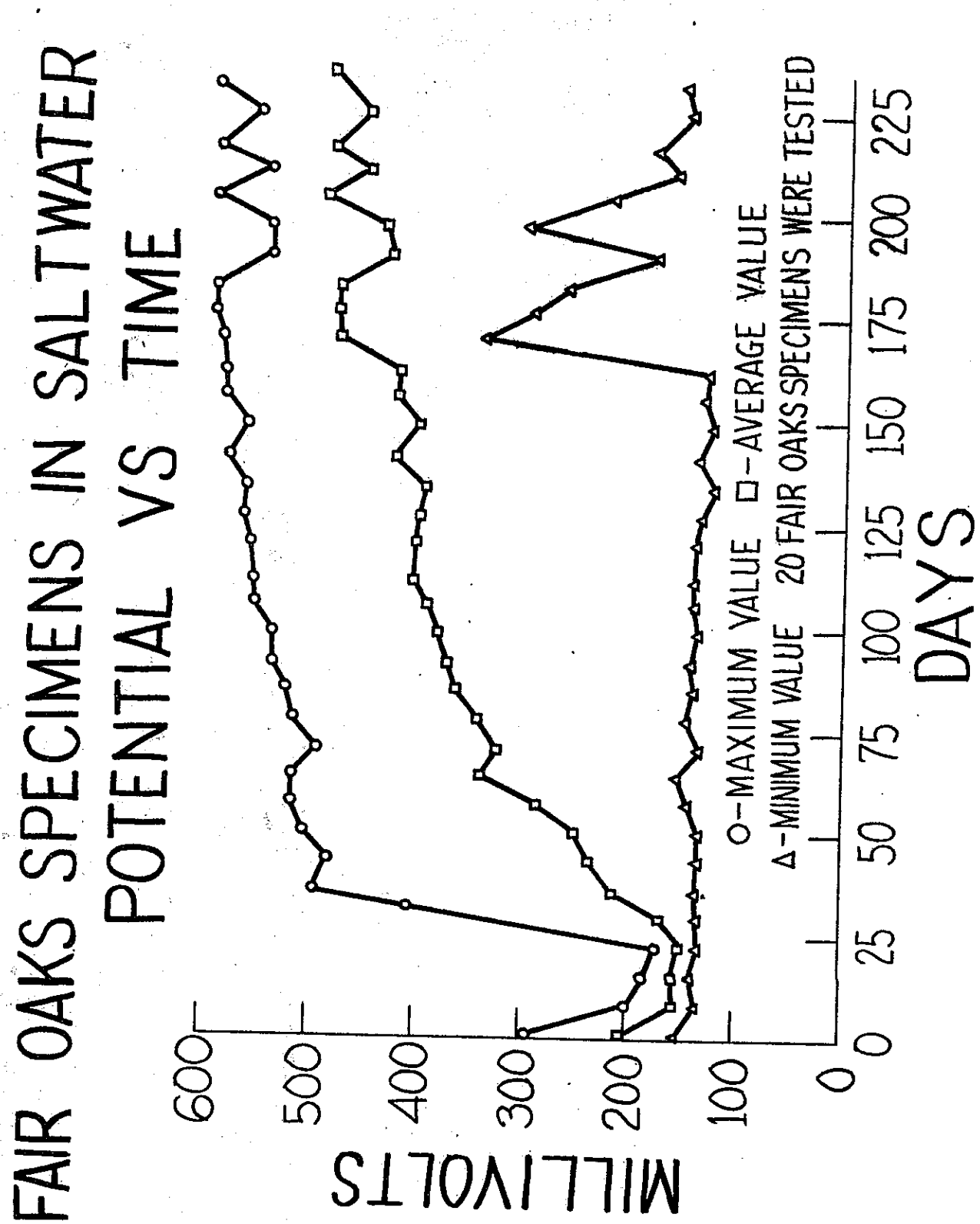

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FIGURE 3

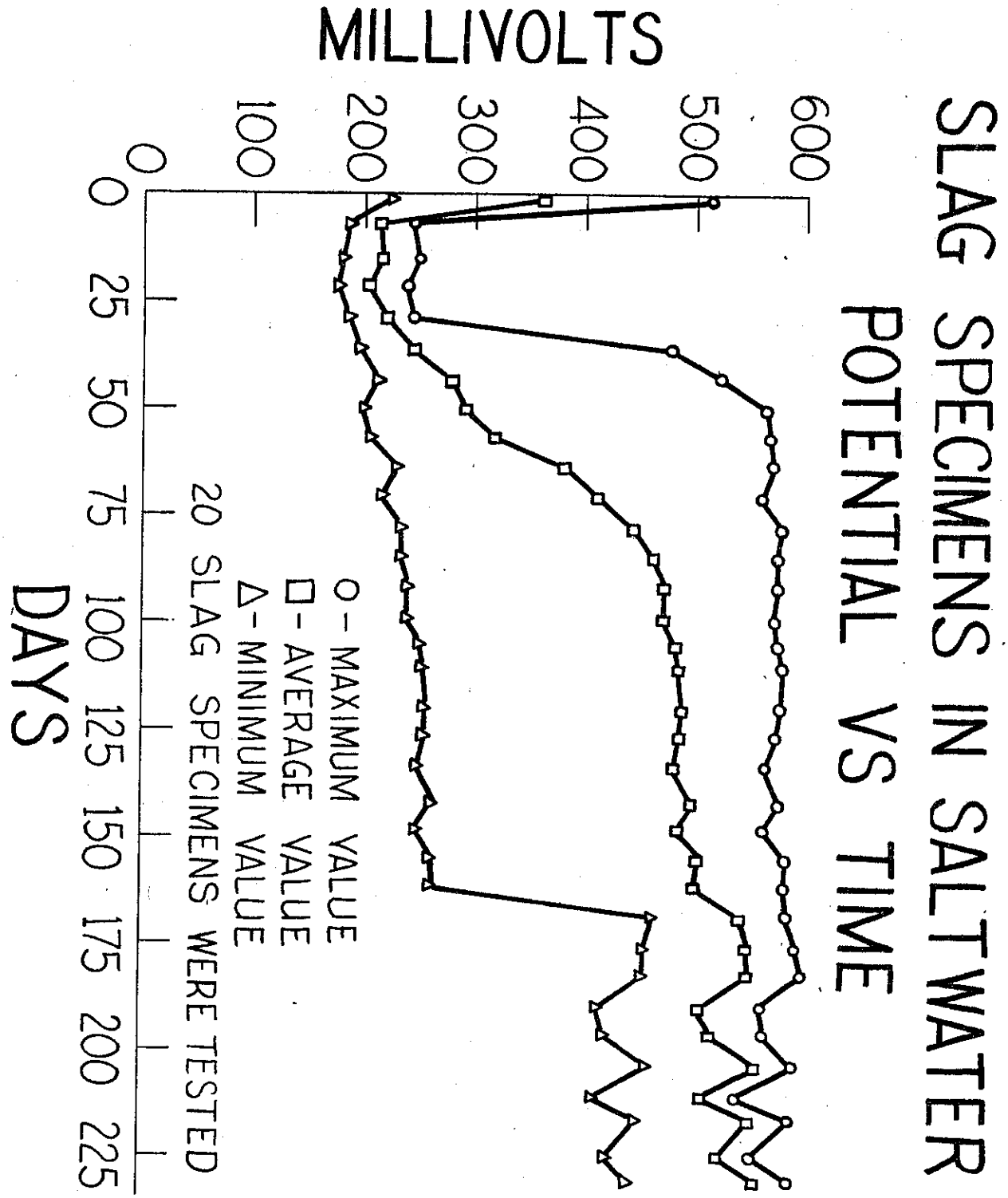

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FIGURE 4

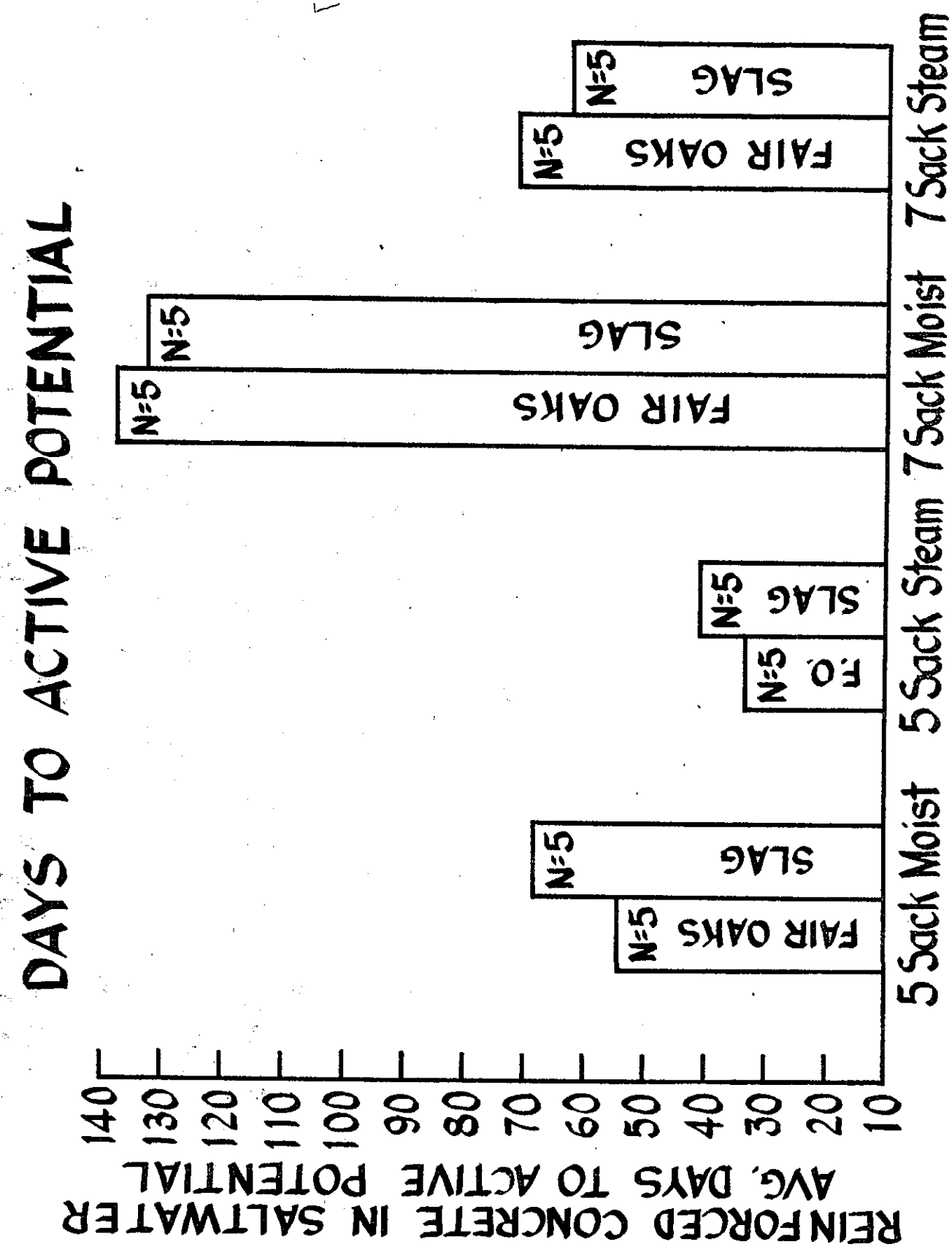

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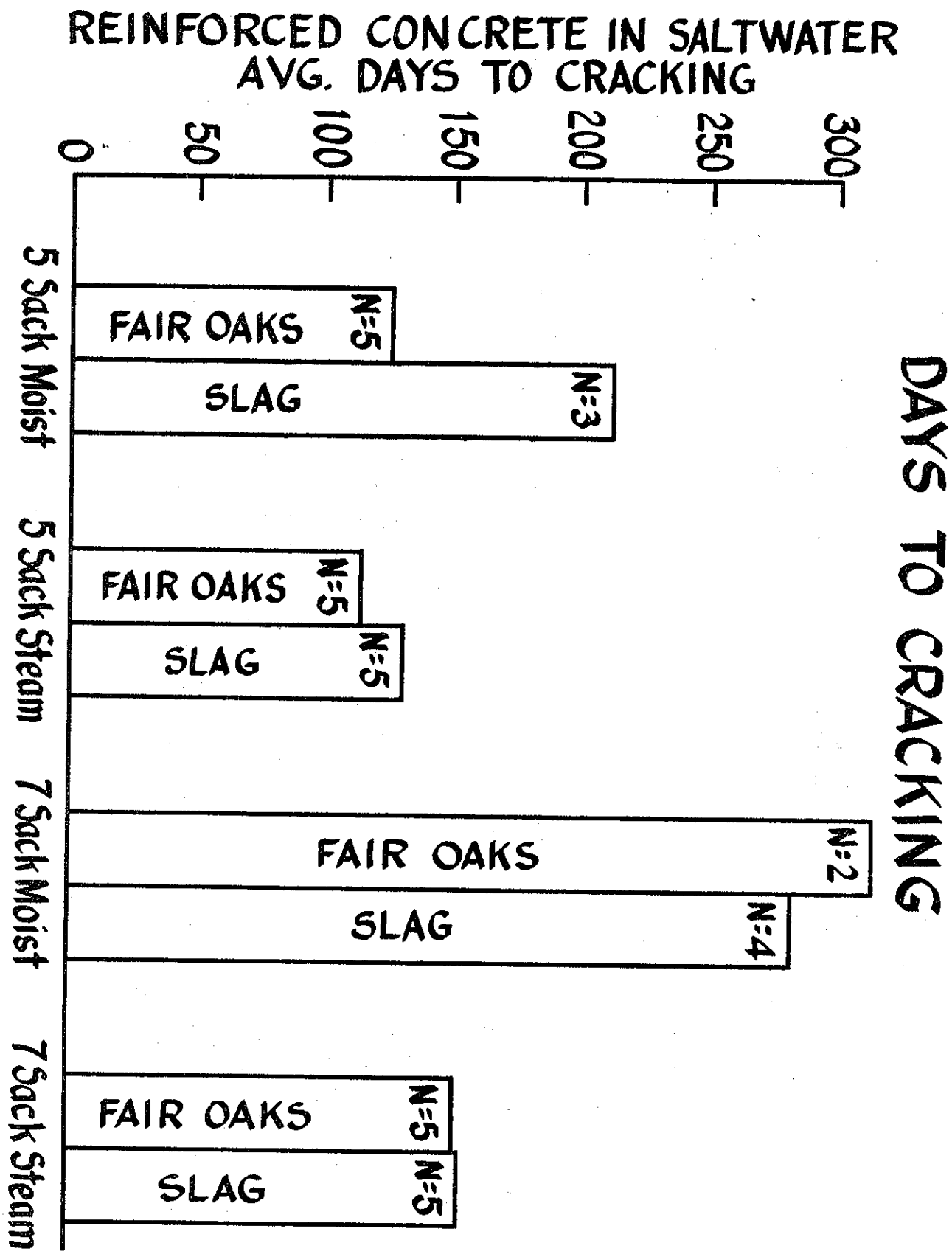
FIGURE 5



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CORROSION RATE OF REINFORCED CONCRETE

CORROSION / SPECIMENS	PIT DEPTH (mils)			SURFACE AREA (in^2)		
	MAX	AVG	MIN	MAX	AVG	MIN
N=15 SLAG (Fontana)	34.0	17.9	9.0	2.59	1.48	0.34
N=16 FAIR OAKS (Natural Agg.)	50.0	22.7	1.0	1.68	0.54	0.01

FIGURE 6

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FIGURE 7

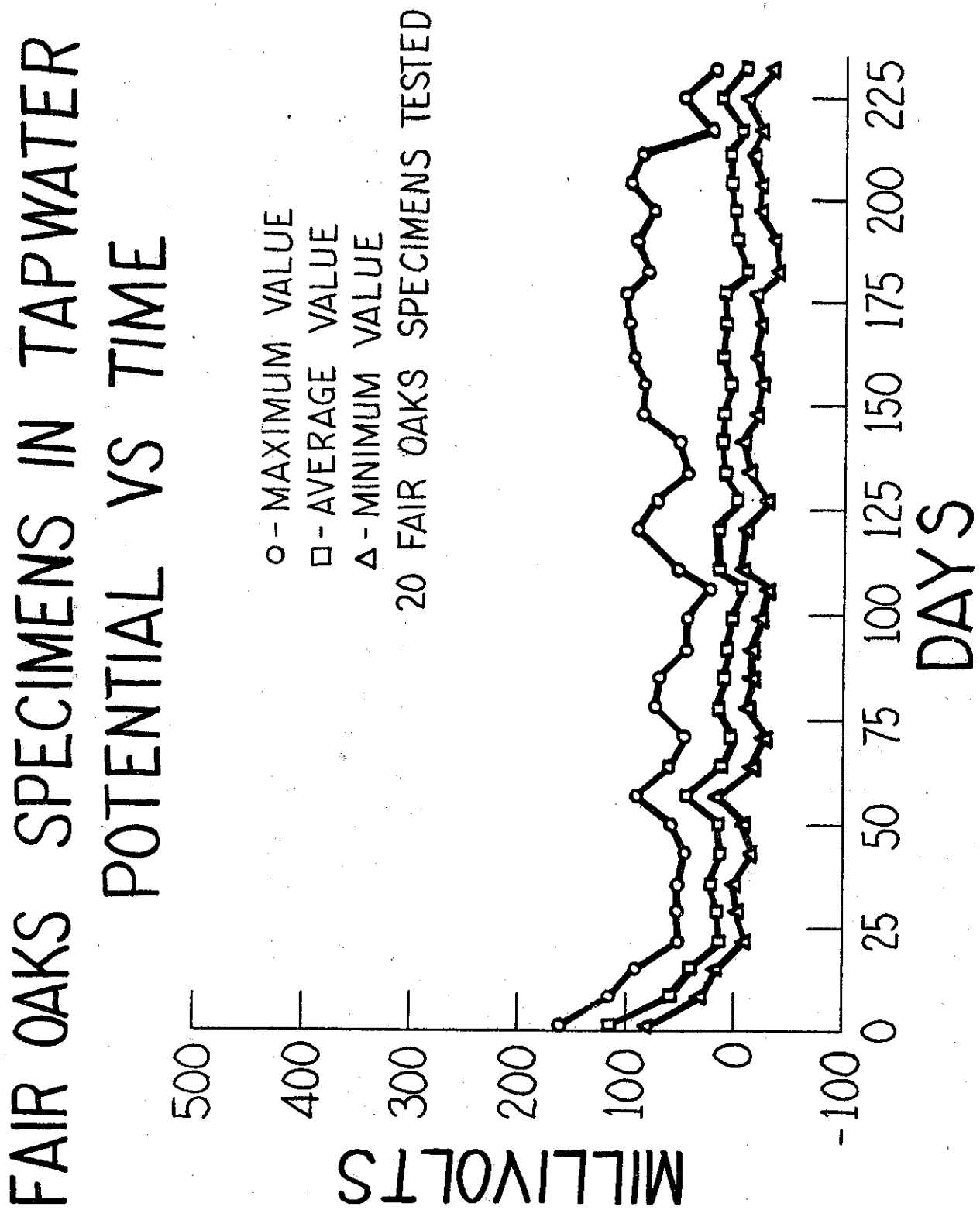

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FIGURE 8

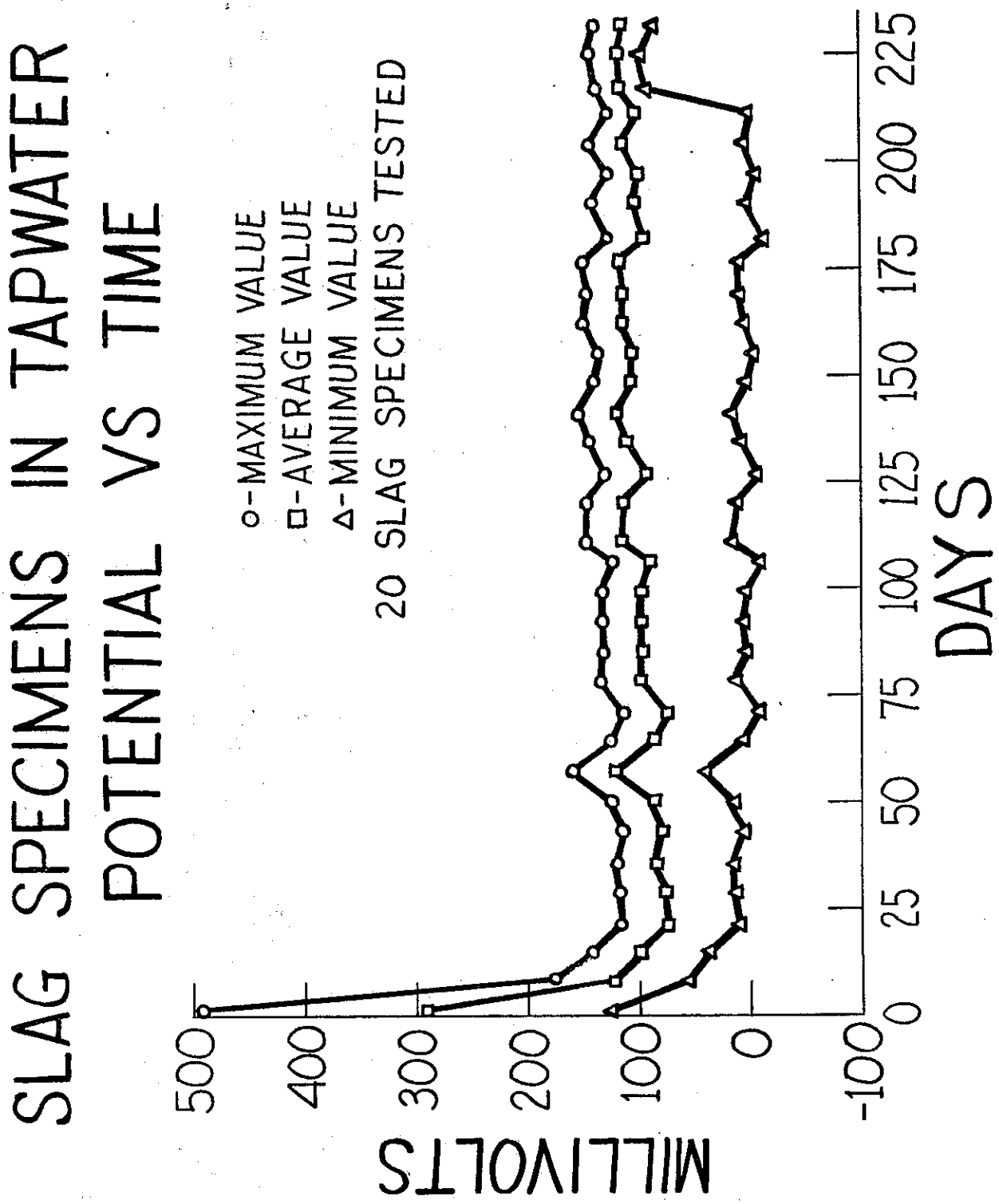

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FIGURE 9

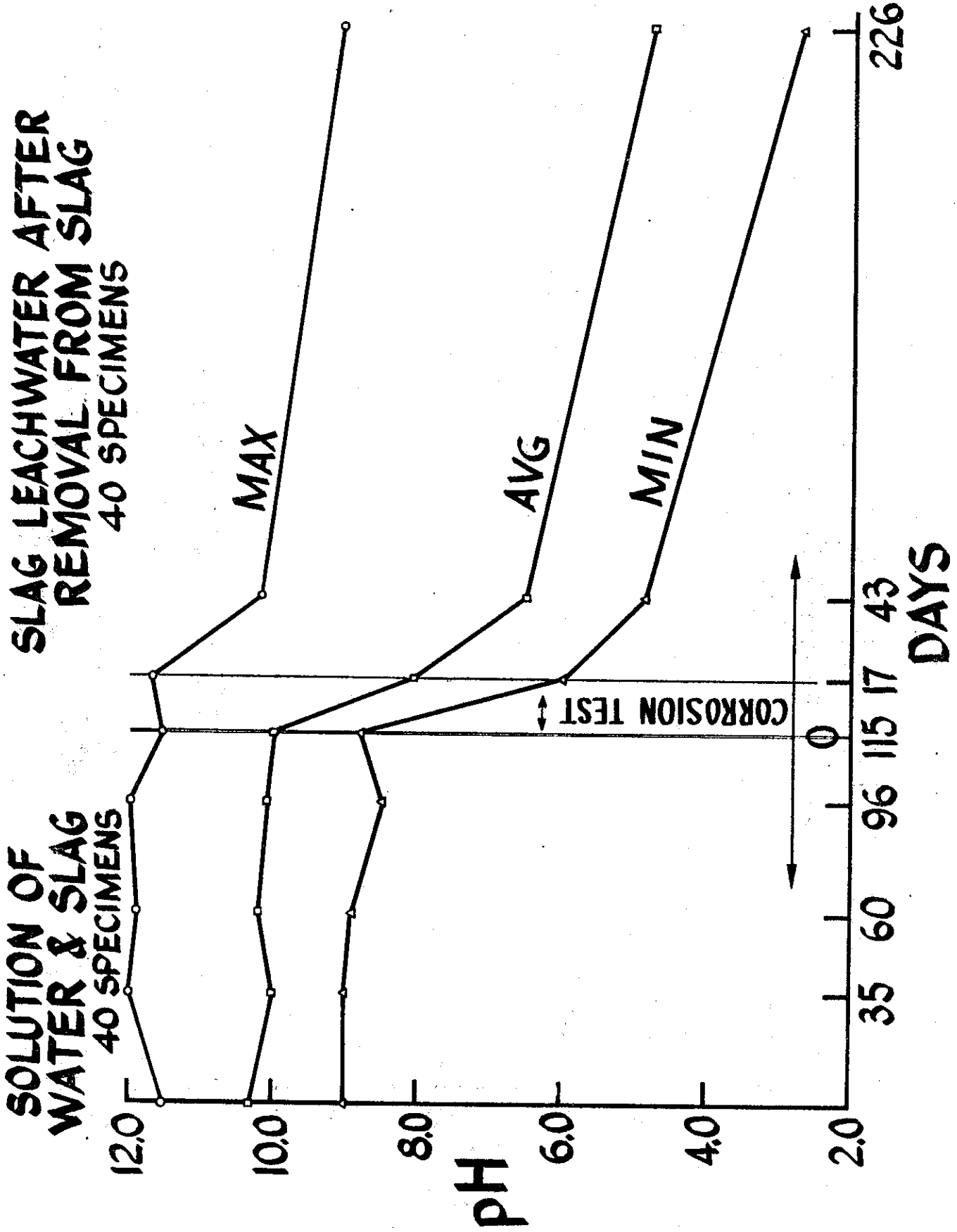

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FIGURE 10

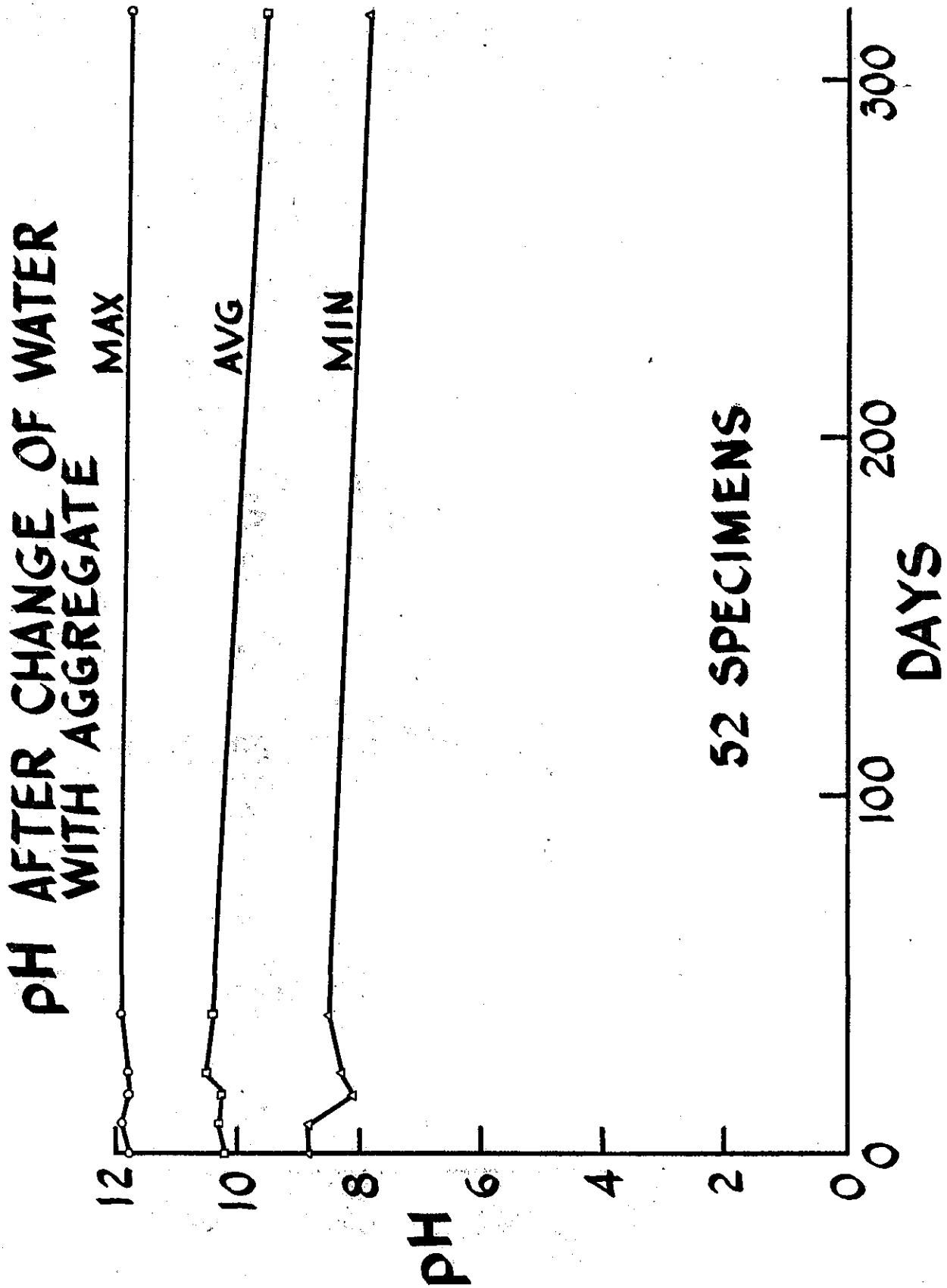

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FIGURE 11

CORROSION RATE OF STEEL (mpy)

IN SLAG SOLUTION WITH AGGREGATE

12 Tests (after 38 days soaking in distilled water.)

MIN	AVG	MAX
0	4.5	10.9

IN SLAG SOLUTION WITHOUT AGGREGATE

52 tests

MIN	AVG	MAX
0.3	4.9	10.0

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