One of the oldest flat roofs that has been waterproofed is the roof of the Carlton Center.in Johannesburg/South Africa The UV-stabilized PU system was applied in 1982 without an additional coating and is still in good condition. Another, better known example is the roof of the Berlin Congress Hall which had to be reconstructed after its collapse in 1980. The area of some 4,000 m² was covered with the flame-retarded system pigmented white (1987). In order to prevent discolouration by UV-radiation, the waterproofing membrane was coated by a PU paint based on aliphatic isocyanates. The terraces and stairs around the Congress Hall have also been waterproofed [5].

Besides the mechanical properties already referred to the key advantage of the system is its ability to be applied without seams. Joints and structures protruding through the roof are sprayed in one operation.

Another application which is now becoming more and more important is waterproofing multi-story car parks. In contrast to conventional techniques, it is not necessary to apply an asphalt layer on top of the PU membrane. It can be replaced by a two-component PU casting resin, which is sprinkled with sand.

All the conventional waterproofing materials used in the International Congress Center in Berlin had to be replaced because they failed after a relatively short time. Some 30,000 m² have been sprayed with the reactive system for repair purposes.

Terracing in sports arenas has been waterproofed with the reactive spray system since 1984. Recently the Olympic Stadium in Helsinki had to be repaired. Some 4,000 square meters have been waterproofed with the flame-retarded PU system, in this case pigmented grey.

Only few tunnel constructions have been waterproofed so far with the reactive spray system. When the tunnels are constructed by open cut, there is no major problem in waterproofing them. The situation is similar to normal bridge decks. However, when the tunnel construction has to be sprayed from the inside, it might be difficult to achieve a watertight membrane with the usual thickness of three millimeters. Especially in the case of sprayed concrete the economical risk of higher raw material consumption has to be taken into account.

Nevertheless, it has been shown recently that tunnels can be waterproofed with spray systems. The roadway in the tunnel under the river Elbe in Hamburg has been successfully waterproofed (14,000 m^2).

Conclusions and prospects

Valuable concrete structures in the building industry can be effectively protected by waterproofing them with highly reactive spray elastomers. The systems described here make an important contribution to durability. Ten years of experience with spray-applied PU elastomers is not very long in terms of the lifetime of a building. But the excellent performance of the material even in this short period of time does encourage more and more decision- makers to profit from applying it.

References

1. Hoscheid, R. (1987) **New Types of Polyurethane Elastomers for the Protection of Concrete and Steel**, Polyurethanes, World Congress 1987, the Proceedings of the SPI/FSK, pp. 434-437.
2. Utsch, R. and Vogel, M. (1992) Spritzbare Polyurethan-Flüssigkunststoffe - **Neuartige Polyurethan-Elastomere als Abdichtung, Oberflächen- und Korrosionsschutz von Bauteilen** in Werkstoffwissenschaften und Bausanierung, Teil 2,Tagungsbericht des dritten Internationalen Kolloquiums zum Thema Werkstoffwissenschaften und Bausanierung (eds prof. Dr. Ing. W. J. Bartz, Technische Akademie Esslingen, Weiterbildungszentrum DI Elmar Wippler, expert Verlag, pp. 929-952).
3. Bayer, Otto et al. (1937) DRP 728981
4. Orth, H. (1955) Kunststoffe-Plastics 2
5. Herold, C. (1987) Das Dachdecker-Handwerk 17, p. 38 - 42 and 18, p. 21 - 25

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The Role of Concrete Mix Design in the Corrosion of Steel in Reinforced Concrete

by M.L. Sennour, H.G. Wheat, and R.L. Carrasquillo

Synopsis: The role of concrete in the corrosion of steel in reinforced concrete has received a considerable amount of attention in recent years. This is due to the recognition of the strong relationship between the nature of the concrete and its ability to protect embedded steel. Therefore, in addition to some of the commonly used corrosion protection methods that focus on either coating the concrete, increasing the cover of the concrete, coating the rebar, or the use of inhibitors that change the nature of the surface of the rebar, other methods should be included that emphasize the role of the concrete mix design.

This paper deals with the contribution of concrete to the corrosion of rebars in reinforced concrete. Twenty six mix designs that represent concretes that could be used today were selected for study. Variables included cement content, water content, amount and type of fly ash, the addition of superplasticizers, and air entrainment. Strength and macrocell current were measured as a function of chloride exposure. The results of one year of cyclical exposure to 3.5 % NaCl solution revealed that the concrete influences the corrosion process greatly. Furthermore, modification of concrete can become another method of corrosion protection through a better understanding of the relationship between the corrosion process and concrete mix design.

Keywords: Admixtures; air entrainment; concretes; corrosion; fly ash; mix proportioning; reinforcing steels; slump; strength; superplasticizers

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INTRODUCTION

The purpose of the research described in this paper is to examine the role that the concrete mix design plays in determining how susceptible reinforced concrete structures will be to corrosion caused by chloride intrusion. In order to do this, a systematic approach has been taken to investigate the corrosion behavior of concrete made with 26 mix designs. In this investigation, measurements were taken to determine the macrocell currents between steel in salt-contaminated and salt-free portions of rectangular prisms subjected to intermittent ponding of sodium chloride solutions. It has been shown that this macrocell current can be associated with the corrosion activity of steel in reinforced concrete (1).

This investigation was part of a much larger investigation in which the corrosion susceptibility was determined by monitoring a number of different parameters such as chloride permeability, chloride penetration, Ecorr (or half-cell potential values) and polarization resistance (which can be directly related to the instantaneous corrosion rates of the steel). In this larger project, all of these factors, in addition to strength and macrocell current were monitored as a function of chloride exposure. This paper focuses on the changes in strength and macrocell current with time and exposure to chlorides.

The mix designs were based on workability and are comparable to mixes that could actually be used today. Because of that, many contain admixtures such as fly ash, superplasticizers, and air entrainment, either alone or in combination. This research offers an opportunity to examine the effects of these admixtures on corrosion tendency. Some of the investigations conducted by other researchers on these and other admixtures are also indicated (2-6).

EXPERIMENTAL PROCEDURE

The experimental procedure involved casting and curing followed by cyclical exposure to chlorides. Throughout the exposure period, changes in strength and macrocell current were monitored as a function of chloride exposure. For the strength tests, the exposure period was 3 days wet and 4 days dry and measurements were taken initially and approximately every other month. For the macrocell experiments, the exposure period was two weeks ponding followed by 2 weeks dry and measurements were taken on the fourteenth day of the wet cycle. The steel used was #4 (0.5" diameter) Grade 60 bar meeting specifications outlined in ASTM A 615. It was cleaned using a sulfuric acid cleaning procedure in order to minimize the variability in the surface condition. The salt solution used for exposure was a 3.5% sodium chloride solution.

For each concrete mix, eighteen 4 x 8" cylinders (used for strength determinations) and three 11 x 6 x 4.5" prisms (used for macrocell current determinations) were cast. The prisms contained one bar about an inch from the top and two bars about one inch from the bottom as shown in Figure 1. The bars were connected with a 100 ohm resistor. Voltage readings made using a high impedance voltmeter were then converted to current using Ohm's Law.

After casting, the specimens were covered and left to set for 24 hours, after which they were stored in an environmentally controlled chamber under 100% relative humidity at 75 °F. They were allowed to cure for 3 or 28 days, depending on the mix. Once the curing period was over, the specimens were put into another environmentally controlled chamber at 40% relative humidity to dry for one week or one week plus 25 days depending on the mix. The effect of curing has been described elsewhere (7,8) and will not be covered in this paper.

The mix designs for the 26 mixes are given in Table 1. The amounts are given in pounds/cubic yard unless otherwise noted. Various amounts of Type C fly ash (containing higher amounts of CaO) and Type F fly ash (containing lower amounts of CaO) are indicated FA. Fly ashes that are either Type C or F are further classified as LOW, MED, and HIGH depending on the actual CaO composition. Selected C and Selected F fly ashes contain CaO compositions which are approximately in the middle of the range with respect to CaO content for either Type C or Type F fly ash, respectively. The use of superplasticizers is noted as SUPER and the use of air entrainment additives that will give 3 to 6% additional air is denoted as AIR. In addition, some mixes are double mixes with one batch cured for 3 days at 100% relative humidity and the other batch cured for the usual 28 days at 100% relative humidity. Double mixes are indicated by the mix number, a hyphen and the number of days curing. Single mixes are indicated with a mix number, a hyphen, and a zero. They were cured for 28 days. Additional specimens from each mix were not subjected to chloride exposure, but were continuously moist cured for one year. All other specimens were allowed to dry in laboratory air for 2 to 4 weeks prior to exposure or ponding. All specimens were subjected to chloride exposure for at least one year. Additional information on the experimental procedure as well as some of the results involving other techniques can be found elsewhere (7,8).

RESULTS

Based on the macrocell currents (in microamps) and strengths (in psi) at one year, various comparisons can be made and various effects can be determined. Examples include the effect of type and amount of fly ash, the effect of superplasticizers, and the effect of air entrainment. These and other effects will be summarized in the figures. Note that Mixes 1-28, 20-28, and 23-28 were made without admixtures. Mix 1-28 is the control mix, Mix 20-28 is a high slump mix, and Mix 23-28 is a high cement content mix.

Effect of Fly Ash

Effect of Type C Fly Ash -- Figure 2 shows that the addition of Type C fly ash containing moderate CaO contents resulted in comparable strength to the control mix, but much lower corrosion activity.

Effect of Type C Fly Ash and Content -- Figure 3 shows that a higher amount of Type C fly ash over 20% resulted in a decrease in strength, but did not change corrosion activity significantly. Mixes 10-0, 6-0, and 8-0 contain 20, 27.5, and 35% Type C fly ash, respectively.

Effect of Type F Fly Ash -- Figure 4 shows that as the CaO content is increased in the Type F fly ash, there is an increase in strength and a decrease in corrosion activity. In addition, there is a significant decrease in corrosion activity compared to the control mix.

Effect of Type F Fly Ash and Content -- Figure 5 shows that the addition of higher amounts of Type F fly ash resulted in an increase in strength and a slight decrease in corrosion activity at 35% fly ash. Mixes 2-0, 4-0, and 11-0 contain 20, 27.5 and 35% Type F fly ash, respectively.

Effect of Superplasticizers

Figure 6 shows that the addition of superplasticizers resulted in strength comparable to the control mix, but a slight decrease in corrosion activity. This is to be expected since Mix 26-28, which contains the superplasticizers, has a low water/cement ratio.

Effect of Fly Ash and Superplasticizers

Figure 7 shows that the combination of superplasticizers and Type C fly ash resulted in excellent behavior. The strength was higher and the corrosion activity was very low. Similar behavior was observed with the addition of Type F fly ash and superplasticizers.

Effect of Air Entrainment

Figure 8 shows that with small quantities of additional air (3% for Mix 14-28), the corrosion activity was actually reduced while with larger quantities, (6% for Mix 15-28), the corrosion activity increased. The strength, as expected, was reduced by the addition of 6% air.

Effect of Fly Ash and Air Entrainment (3%)

Mix 14-28 was made without fly ash, while Mixes 16-0 and 18-0 were made with 27.5% Type C and F fly ash respectively. Figure 9 shows that while the strength of the concrete made with Type C and Type F fly ash was decreased with 3% air, the corrosion activity was almost unchanged.

Effect of Fly Ash and Air Entrainment (6%)

Mixes 15-28, 17-0, and 19-0 were all made with approximately 6% entrained air. Mix 15-28 contained no fly ash, while Mixes 17-0 and 19-0 contained 27.5% Type C and F fly ash, respectively. Figure 10 shows that the strengths were comparable for the three concretes. The incorporation of Type C and F fly ash in high air entrained concretes, however, resulted in a considerable reduction in the corrosion activity.

Effect of High Water Content (High Slump)

Figure 11 shows the effect of high slump concrete. The slump is given beside the name. For example, 20-28 NO FLY ASH 7" indicates a 7 inch slump for Mix 20-28. The high slump conventional concrete exhibited the highest corrosion activity. Even though the slumps for Mixes 21-0 and 22-0 were also high, the addition of Type C fly ash in Mix 21-0 and Type F Fly ash in Mix 22-0 resulted in a reduction in corrosion activity. The reduction was larger in the case of the Type F fly ash.

Effect of High Cement Content (High Strength)

Figure 12 shows the effect of high cement content and thus high strength concrete. Since cement is the strength controlling factor, its higher content resulted in higher strength. In addition to higher strength, much lower corrosion activity was observed. The addition of Type C and Type F fly ash to high cement concretes led to even higher strengths and virtually no corrosion activity.

It should be pointed out that at the end of one year, one specimen from each mix was opened to observe the condition of the steel and in all cases, corrosion was observed when corrosion activity had been predicted based on macrocell current flow.

CONCLUSIONS

The results reported above have shown the effects of a number of variables on the tendency for corrosion in reinforced concrete. In addition, the results show that concrete mixes can be designed to minimize corrosion. This research has been carried out in a very systematic way and it has involved assessing the corrosion tendency of concrete mixes that are comparable to mixes that would be used today. This assessment of corrosion tendency has been made by using macrocell current as a measure of corrosion activity. As mentioned, this investigation is part of a much larger investigation in which other techniques are also being used to examine corrosion tendency. Earlier comparisons of the results of the different techniques showed that measurements of macrocell currents are very beneficial in evaluating the corrosion tendency of various concrete mixes.

The findings of this investigation demonstrate that in addition to other protective measures such as the use of sealers on concrete, protective coatings on reinforcing bars, and cathodic protection of steel in concrete, one very powerful weapon to minimize corrosion is the design of the concrete itself.

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REFERENCES

1. Berke, N.S., M.P. Dallaire, M.C. Hicks, and R.J. Hoopes, "Corrosion of Steel in Cracked Concrete," Paper 322, Corrosion '93, National Association of Corrosion Engineers, 1993.

2. Protective Systems for New Prestressed and Substructure Concrete, U.S. Department of Transportation, Federal Highway Administration, Report No. FHWA/RD-86/193, 126 pp., April 1987.

3. Nmai, C.K. and E.K. Attiogbe, "Effect of Chemical and Mineral Admixtures on the Corrosion of Steel in Concrete," Paper 201, Corrosion '92, National Association of Corrosion Engineers, 1992.

4. Berke, N.S., "Microsilica and Concrete Durability," Portland Cement Concrete Modifiers, Transportation Research Record, No. 1204, pp. 21-26, Transportation Research Board, 1991.

5. Berke, N.S., M.J. Scali, and J.C. Regan, "Long-Term Corrosion Resistance of Reinforcing Steel in Silica Fume Concrete Exposed to Marine Environment," Durability of Concrete, Second International Conference, Montreal, Canada, American Concrete Institute, SP-126, Vol. 1, pp. 479-497, 1991.

6. Rose, J., "The Effect of Cementitious Blast-Furnace Slag on Chloride Permeability of Concrete," Corrosion, Concrete, and Chlorides-Steel Corrosion in Concrete: Causes and Restraints, American Concrete Institute, SP-102, pp. 107-126, 1987.

7. Sennour, M., H. Zhang, H.G. Wheat, and R.L. Carrasquillo, "Corrosion of Steel Bars in Concrete Containing Different Chemical and Mineral Admixtures,": Paper 199, Corrosion '92, National Association of Corrosion Engineers, 1992.

8. Sennour, M.L., H. Zhang, H.G. Wheat, and R.L. Carrasquillo, "Corrosion Susceptibility of Concrete Made with Chemical and Mineral Admixtures," Paper 337, Corrosion '93, National Association of Corrosion Engineers, 1993.

TABLE 1 — FRESH CONCRETE PROPERTIES AND CONCRETE MIXTURES

MIX	CEMENT	F A	TYPE	%	ROCK	SAND	WATER	Admxt	TYPE	TEMP	R H	Crt T	SLUMP	AIR	W/C
1	591	0			1387	1693	388			89	64	94	4.5	3	0.66
2	532	85	Low F	20	1565	1965	370			71	60	56	4	3	0.60
3	473	93	High F	20	1375	1615	373			90	60	98	3.5	3	0.66
4	482	117	Low F	27.5	1565	1965	370			71	60	56	4	3	0.62
5	438	131	High F	27.5	1415	1800	285			70	44	74	3	3	0.50
6	402	123	Low C	27.5	1285	1750	365			87	60	96	5.5	3	0.70
7	425	144	High C	27.5	1390	1724	281			76	65	62	4	3	0.49
8	378	164	Low C	35	1353	1659	366			90	60	94	4.5	3	0.68
9	381	183	High C	35	1390	1724	281			76	65	63	4.25	3	0.50
10	483	99	Medium C	20	1401	1754	305			83	40	90	3.75	3	0.52
11	385	153	Medium F	35	1372	1619	371			84	64	86	4	3	0.69
26	583	0			1359	1785	270	70 oz	SUPER	76	58	77	3.5	3	0.46
12	430	134	Medium C	27.5	1377	1836	286	68 oz	SUPER	90	52	93	3	3	0.51
13	433	122	Medium F	27.5	1387	1831	283	67 oz	SUPER	89	54	92	3.5	3	0.51
14	615	0			1437	1646	277	45 ml	AIR	58	46	62	3.25	6.5	0.45
15	641	0			1506	1742	258	135 ml	AIR	65	78	71	5.75	9	0.40
16	429	133	Medium C	27.5	1452	1453	307	89 ml	AIR	70	55	72	5.5	6.75	0.55
17	429	133	Medium C	27.5	1452	1453	307	133 ml	AIR	71	50	72	4.5	9	0.55
18	438	123	Medium F	27.5	1418	1518	240	59 ml	AIR	58	46	63	3.5	6.25	0.43
19	438	123	Medium F	27.5	1418	1518	240	91 ml	AIR	58	46	64	3	8.5	0.43
20	599	0			1395	1647	408			72	62	74	7.25	3	0.68
21	432	135	Medium C	27.5	1395	1647	401			68	80	84	7.25	3	0.71
22	432	122	Medium F	27.5	1395	1647	401			68	80	85	8.25	3	0.72
23	801	0			1385	1456	369			84	64	86	8.5	3	0.46
24	568	174	Medium C	27.5	1366	1396	351			85	60	94	7	3	0.47
25	568	158	Medium F	27.5	1365	1395	350			85	60	93	8.5	3	0.48