

Corrosion Studies Relating to Precast Spliced Piles

by

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Introduction

Precast concrete pile foundations are invariably used in soils of low bearing capacity. When the load bearing hard strata lies very deep, the conventional precast concrete piles become very long and handling becomes difficult. To facilitate easy handling, precast members can be cast in modules of standard lengths (approximately 10 m each) and can be joined using metallic splices. This precast spliced piles technology was developed in 1960s (Cederwell, 1962, Severinson, S. 1965, and Stabilator, A.B. 1969). In the case of precast spliced piles, the metallic splices are exposed to a variety of environments like acidic soils, soils rich in chloride, sulphate or sulphate reducing bacteria, etc. Under such exposures to corrosive soils splice materials need additional protection, to ensure the durability of piles. Pile joints in fill soils, cinders, marine clays or reclaimed soils will undergo severe corrosion. Therefore corrosion resistance of splice materials has to be evaluated before selecting the cost effective one. Corrosion of splice was identified as a major problem by many workers [Bruce, *et al* 1974, Bartholomew, 1979, and Bamber, 1981].

Many incidences of corrosion of steel piles driven in soils have been reported. Consolidated data from literature on corrosion of steel piles in soil is presented in Table I. Eventhough one would normally expect corrosion of steel to be negligible at greater depths because of oxygen starvation, incidences quoted show that even at a depth of 37.5m below ground level significant corrosion (0.134mmpy) can occur. Steel piles exposed for six years in fill soil corroded to the extent of 152 mils i.e. at the rate of 1.0 mmpy (Kinson, *et al* : 1981). In another incidence, piles exposed to industrial fill soil environment suffered to the extent of 0.27mmpy. In a

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TABLE I

Corrosion of Steel Piles buried in Soil

Location	Nature of Soil	Exposure period (yrs.)	Total corrosion (mils)	Corr. rate (mmpy)	Ref.
Coke Oven Batteries,	Fill soil	6	152.4	1.00	Williams (1964)
Australia Norway	Marine clay	6.5	100.10	0.39	Tungesvik et al (1975)
Grenada Dam Spillway, Site A	Sandy loam	6.5	172.00	0.38	Romanoff (1957)
Australia	Industrial Fill	34 w 49 w	6.95 8.24	0.27 0.22	Williams (1959)
Oslo East Station 'B'	Fill soil	...	...	0.45	Tungesvik et al (1975)
Oslo East Station 'C'	-do-	...	...	0.40	-do-
Oslo East Station	Fill soil silty clay	...	...	0.30	-do-
Grenada Dam	Fill soil silty sand	...	...	0.39	Romanoff (1957)
Maryland USA	gravel & sand (37m)	18.0	95.4	0.13	-do-

17 year study, steel piles were found to have corroded maximum at the ground water level. Above the ground water level, corrosion was dependent on chloride/sulphate concentration (Tanaka, : 1990). A good correlation of sulphate content and corrosion has been observed. It has been found that sulphide ions can produce pitting in steel exposed to a passive medium like saturated calcium hydroxide (Morgan, : 1989).

The form of corrosion is equally important. Highly localised corrosion like pitting or crevice corrosion can be dangerous. Data presented in Table II give credance to the fact that not only general corrosion, but severe pitting can also occur in soil. Cinders, high alkali soils and marine soils exhibited severe corrosivity.

It goes without saying that the splice materials which are normally made of mild steel (on cost considerations) need additional protection before they are buried in an aggressive soil environment. In this regard either an alternative material of better corrosion resistance may be considered or a cost effective and durable protective system identified.

TABLE 2
Corrosion of Steel Buried in Soil

Location	Nature of soil	Duration (yrs)	Total Corr. (mils)	Corr. rate (mmpy)	Reference
NBS Survey	Cinders, clay	10.0	95.0 150.0	0.24 1.90*	Romanoff (1957)
Pant Eidel U.K.	Marine soil	0.5	3.8 30.6	1.90 1.55*	Booth et al (1969)
Dovy Inl. U.K.	Marine soil	0.5	5.02 30.50	0.256 1.55*	Booth et al (1969)
California, USA	Clay with high alkali	5.9	198.0	0.85*	Romanoff (1962)
South End UK	Mud	1.0	6.4 37.4	0.16 0.95*	Booth et al (1969)
Goa, India	Mud	30 d 90 d	0.4 3.0	0.125# 0.305#	Patil et al (1989)

*Pitting corrosion

#Bacterial attack

Low alloy steels have been considered as better corrosion resistant alternatives for mild steel in many applications (Schmitt, and Gallagher, : 1969, Vrable, *et al*, : 1979). Some of the low alloy steels have been found to undergo severe pitting and general corrosion in soil environment [Cobourn, : 1978].

Many protective systems like organic coatings, wrapping and metallising have been tried for piles (Romanoff, : 1962, Alumbough, : 1964, Kumar, and Wittmer, : 1979). Cathodic protection of splices has been tried using sacrificial anodes. (Bamber, : 1979). Jacketing of splices for protection has been reported to be unsuccessful (Bamber, : 1979).

Steel embedded in precast spliced piles also need additional protection for the following reason : during pile driving operations considerable impact force is imparted. Microcracks are formed within concrete during driving operations (Fellinius, : 1974) This may increase the porosity of concrete and thus affect the durability of steel in concrete (Subramanian, *et al*. 1990).

In the present work, studies have been carried out on the corrosion resistance of mild steel and three alternative materials, namely a copper bearing

dual phase steel and two microalloyed high strength low alloy (HSLA) steels. Different protective schemes for mild steel splice material, based on powder epoxy, polyurethane and liquid epoxy systems, metallising (flame sprayed aluminum) and an inorganic cement based coating have been investigated for their performance under both laboratory and field simulated conditions.

Protective schemes for concrete surface have also been evaluated for their performance under the action of impact blows.

Experimental/Investigations

Studies on alternate materials

In addition to mild steel, other materials studies; (i) 0.28% copper bearing dual phase steel (ii) 0.2% micro alloyed HSLA steel (iii) 1.3% micro alloyed HSLA steel. The chemical composition and mechanical properties of these materials are given in Table 3 and 3A. For all the tests the specimens were mechanically polished, washed, degreased with trichloroethylene and dried. In all electrochemical tests, saturated calomel reference electrode and Platinum auxiliary electrodes were used.

Evaluation of General Corrosion Resistance :

General corrosion resistance of the materials were evaluated by Tafel extrapolation method (Dean, S.W. Jr. *et al.* : 1971). By this method the corrosion current density (I_{cor}) can be obtained from which the corrosion rate of the material in the test medium can be calculated. The test material (working electrode) was polarised in cathodic and anodic directions using EG&G Potentiostat and a Scan Generator. E-log i plot was recorded using a Rikadenki X-Y-t recorder. Corrosion current density (I_{cor}) was

TABLE 3

Chemical composition of materials tested

Material	C	Mn	Si	P	Cu	S	Sn	Micro alloying
Dual Phas steel	0.2	1.00	0.4	0.05	0.3	—	0.03	Nil
HSLA 3	0.2	1.0	0.5	0.04	—	0.04	—	0.20%(Nb, Ti, V,B)
HSLA4	0.2	1.5	—	0.04	—	—	—	0.3%(Nb, V, Ti)

TABLE 3A

Mechanical properties of materials tested

Material	Yield strength (N/mm ²)	U.T.S. (N/mm ²)	Elongation %
Mild steel	296	435	22.6
Dual phase steel	502	652	12.2
HSLA 3	410	540	11.0
HSLA 4	427	570	24.0

obtained by extrapolating the anodic and cathodic polarisation curve. Corrosion rate of the material in mmpy was deduced from Icor.

Evaluation of Pitting Corrosion Resistance :

Pitting corrosion resistance of the materials in different environments was studied using (i) galvanostatic anodic polarisation technique (ii) Peak potential technique and (iii) potentiodynamic anodic polarisation technique.

Galvanostatic anodic polarisation technique

This technique enables one to find the tolerable chloride limit for the different material/environment systems. This is an accelerated electrochemical test which can be completed in five minutes (Rajagopalan, K.S. *et al* : 1962). After passing an anodic current of 290 $\mu\text{A}/\text{cm}^2$ to the working electrode (test material), the potential-time behaviour was studied for five minutes. A drop in potential from oxygen evolution potential is indicative of pitting. Critical concentration of chloride beyond which pitting occurs is termed as tolerable chloride limit.

Peak-potential technique

This is a near-realistic test to find out whether the given environment can cause pitting (Rajagopalan, K.S. *et al* : 1977). The test duration is one hour. Potential-time behaviour is studied for one hour. Using a potentiostat, the specimen was kept at its maximum positive open circuit potential, namely, its peak potential. A rapid increase in current flow was indicative of pitting. Tolerable chloride limit, beyond which pitting occurs was found.

Potentiodynamic anodic Polarisation technique

This technique can be used to compare the materials for their pitting resistance. By polarising anodically, the test material is taken to a sufficiently

noble potential to cause pitting. The potential at which pitting is initiated is termed as critical pitting potential. The more positive the critical pitting potential (EC_p), greater is the pitting resistance of the material (Dean, Jr. : 1971).

After introducing the specimen into the test solution, the open circuit potential (OCP) was monitored till a steady state was achieved. The working electrode (test material) was polarised at a scan rate of 1mv/sec to a sufficiently noble potential to cause pitting and critical pitting potential was determined.

Sulphide Stress Corrosion Cracking Tests :

Susceptibility to sulphide stress cracking was evaluated using tensile specimens of length 150mm and diameter of 7mm with 20mm gauge length of reduced diameter of 3mm. Except the gauge length portion, rest of the specimen was marked. Specimens were subjected to a tensile stress equal to 90% of proof stress, using a spring loaded arrangement. Hydrogen sulphide saturated 5% sodium chloride solution at $pH=3.0$ was introduced into the cell. H_2S gas was purged continuously to maintain saturation. Test duration was 500 hours. Any failure within the period was noted. Test was done at 80% proof stress also.

Evaluation of Protective Schemes :

Different commercially available coatings were tested for their performance in laboratory and field simulated conditions.

Performance of coatings in aggressive media—Laboratory Studies I

In order to find out the extent of corrosion of mild steel in different media weight loss measurements were done using 4.5×1.0 cm mechanically polished mild steel specimens under deaerated conditions in tap water, 1% NaCl solution, H_2S saturated water and H_2S saturated 1% NaCl solution. Corrosion rate was calculated by weight loss measurements.

Similar experiments were carried out in H_2S saturated 1% NaCl solution (deaerated) with coated specimens to evaluate different coating systems. Efficiency of different systems was calculated on the basis of weight loss.

Field Exposure Studies :

Mild steel panels of size $100 \times 100 \times 10$ mm were used for field exposure studies for evaluating the relative performance of different protective coatings. Specimens were grit blasted, degreased with trichloroethylene, coated with different systems, air cured for a specific period and driven into soil to a depth of 1m below ground level. In order to make the soil environment very aggressive, sulphide in the form of H_2S saturated 1%

NaCl solution was added periodically, using a percolation system as shown in Fig. 1. Specimens were exposed for 6 months after which they were retrieved and examined for the extent of rusting. Corrosion resistance of coating systems were determined by measuring percentage rusted area.

Durability factor of each system was worked out as the ratio of percentage without coating to the percentage area rusted with coating. Ratio of the durability factor to unit cost of the system was taken as "Cost-Benefit Ratio" which is considered as the ultimate factor for grading of protective system.

Effect of Impact

In order to understand the effect of impact on corrosion of steel in concrete, experiments in triplicate were done using a miniature drop hammer system imparting an impact energy of 160 kg cm per blow at a height of fall of 50 cm.

Mild steel specimens of diameter 6mm and length 70 mm were mechanically polished, degreased and weighed. Specimens were embedded in M40 grades concrete of size $10 \times 10 \times 20$ cm with a clear cover of 21 mm as shown in Fig. 2. After 28 days curing, the specimens were first subjected to blows and then to alternate wetting in 3% sodium chloride solution and drying, for 60 days. After the test period, rebars were removed, pickled and corrosion rate was calculated on the basis of weight loss.

In another set of experiments, five different concrete surface coatings were tested for their performance under impact. Coated reinforced concrete specimens were given 1500 blows and later subjected to alternate drying and wetting in 3% sodium chloride solution. After the test period of 60 days the weight loss of the mild steel rebar was determined. Efficiency of the protective schemes was deduced.

Results and Discussion

Studies on Alternate Materials

Corrosion rate of the materials under consideration in different aqueous media is presented in Table 4. Copper bearing steel behaves almost similar to mild steel. From the values of durability factor given in Table it is evident that microalloyed HSLA steels are 1.6 to 5.7 times more corrosion resistant. It has been reported that the addition of copper did not impart any corrosion resistance in the case of steel piles in soil [Ohsaki, : 1972]. Perhaps Cu-bearing steel may be suitable only for atmospheric exposures.

From the chloride tolerable limits obtained from galvanostatic anodic polarisation technique and peak potential technique, it has been found that microalloyed HSLA steels have very high tolerable limits (Table 5).

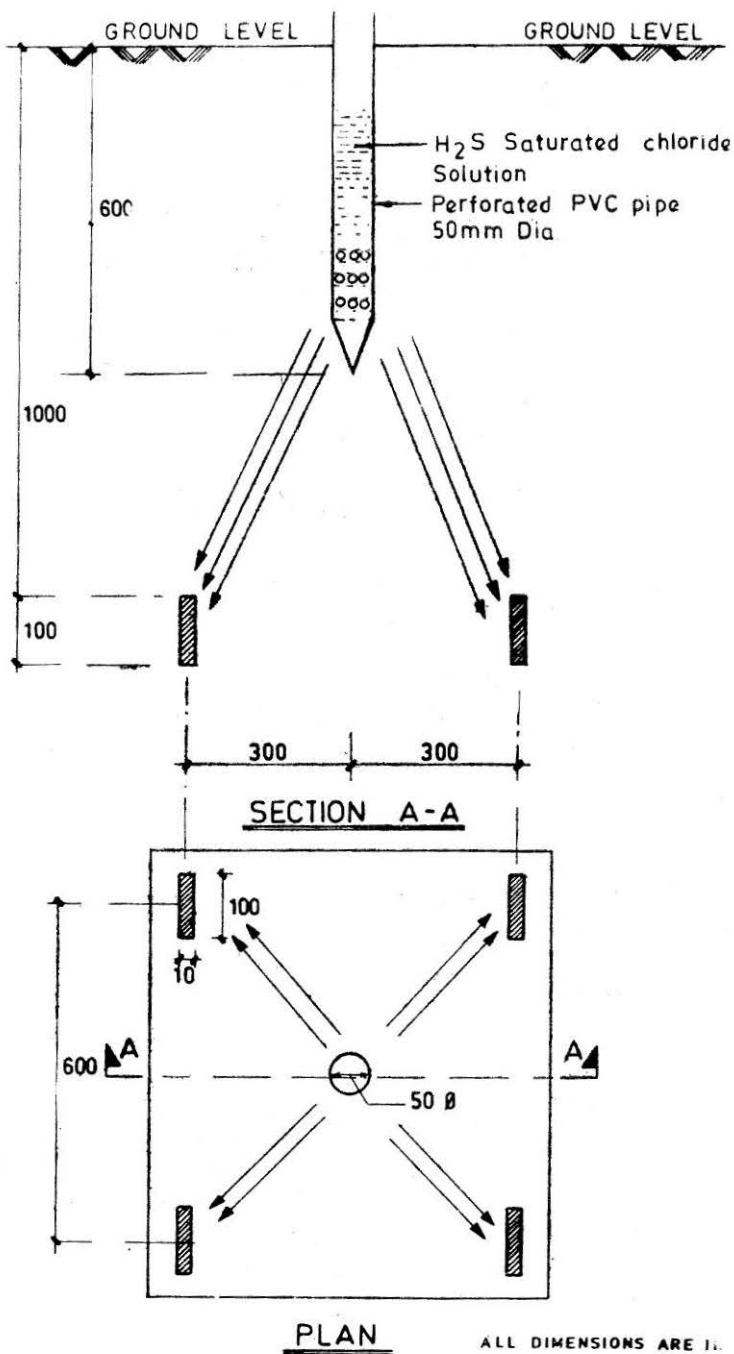
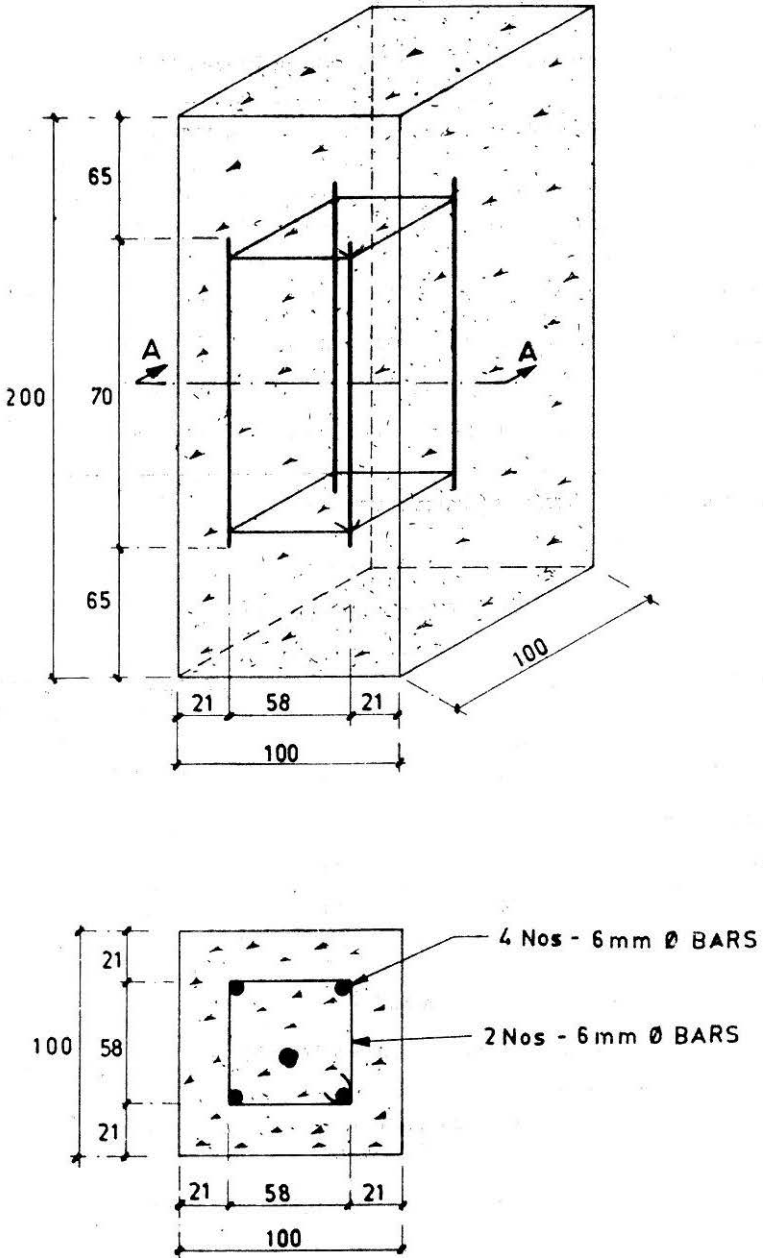


FIGURE 1 Field Exposure Studies On Driven Steel Plates Along with Percolation System

**SECTION AT A-A**

ALL DIMENSIONS ARE IN mm

FIGURE 2 Concrete Specimen Used For Impact Studies

TABLE 4

Corrosion rate of Splice Materials in different Media

Material	Tap Water		3% NaCl		0.04 N NaOH +1% NaCl		0.04N NaO +1% NaCl	
	Icor	C.R.	Icor	C.R.	Icor	C.R.	Icor	C.R.
Mild steel	2.60	1.19	72.76	33.4	1.04	0.478	1.35	0.63
Cu-bearing steel	2.59	1.19	70.42	32.09	0.87	0.399	1.66	0.76
HSLA 3	0.73	0.33	21.30	9.78	0.29	0.131	0.52	0.23
HSLA 4	0.67	0.31	12.69	5.84	0.19	0.086	0.47	0.22

Icor in mA/cm² Corr. rate (CR) in mmpy

TABLE 4 A

Durability factor based on corrosion rate

Material	Tapwater	3%NaCl	0.04N NaOH +1% NaCl	0.04N NaOH +0.1% NaCl
Mild Steel	1.00	1.00	1.00	1.00
Cu-bearing steel	1.00	1.04	1.197	0.817
HSLA 3	3.57	3.42	1.67	2.70
HSLA 4	3.88	5.73	5.53	2.82

TABLE 5

Tolerable Chloride limit in 0.04N NaOH (in ppm)

Material	Galvanostatic anodic Polarisation		Peak potential Technique	
	Inhibitive	Corrosive	Inhibitive	Corrosive
Mild Steel	100	135	750	1000
Cu-bearing steel	200	250	1000	1200
HSLA 3	275	300	6500	7000
HSLA 4	300	325	9000	10000

Critical pitting potentials of the materials in chloride added 0.04N NaOH media are given in Table 6. HSLA 4 exhibits very good pitting resistance with over 100 mV more positive Ecp values. Cu-bearing steel does not exhibit any significant improvement in pitting. The reason for such high pitting resistance of micro alloyed HSLA steels may be attributed to their ability to form a tightly adhering passive film [Schumacher : 1979]. Rare earth oxides and carbides improve the texture of the passive film.

Failure time of the test materials in H₂S saturated chloride is presented in Table 7. Mild steel shows better sulphide stress corrosion resistance compared to the alternate candidate materials. HSLA steels show shorter failure time.

Increased susceptibility to sulphide stress corrosion of HSLA steels may be due to their increased strength. It has been established already that susceptibility to stress corrosion increases with increase in strength and hardness (Phellps, : 1967). Therefore, from the point of view of sulphide stress corrosion, one has to prefer mild steel for splicing.

TABLE 6

Critical Pitting Potential measurements

Material	0.04 NaOH+50ppm Cl		0.04N NaOH+100 ppm Cl	
	OCP (mv)	Ecp (mv)	OCP (mv)	Ecp (mv)
Mild steel	-291	660	-260	655
Cu-bearing steel	-322	667	-247	660
HSLA 3	-242	698	-214	699
HSLA 4	-351	772	-323	767

TABLE 7

Time-to-failure for splice materials at 90% proof stress in H₂S saturated 5% NaCl at pH= 3.0

	Mildsteel	Cu-bearing steel	HSLA 3	HSLA 4
Time-to-failure (hrs)	162+10	107+10	56+5	128+2

Evaluation of Protective Schemes

Corrosion rate of mild steel in different media under deaerated conditions is given in Table 8. It has been found that even in the absence of oxygen, which is the condition likely to be encountered in deep soil, mild steel corrodes at a rate of 0.316 mmpy in the presence of hydrogen sulphide and chloride.

Eight different protective systems were tested for their efficiency in deaerated, H₂S saturated 1% NaCl solution by weight loss method. Except for a few many systems showed blistering of coating (Table 9). Cement based inorganic coating and metallising (flame sprayed aluminium) exhibited 100% efficiency followed by Powder epoxy system IV (with greenish grey finish) with 90.7% efficiency. All these three systems did not

TABLE 8

Corrosion rate of mild steel in different media under de-aerated Condition

Medium	Corrosion rate (mmpy)
Tap water	0.030±0.001
1% NaCl soln.	0.056±0.001
H ₂ S saturated water	0.293±0.008
H ₂ S saturated 1% NaCl	0.316±0.023

TABLE 9

Efficiency of different Protective Systems in Deaerated H₂S Saturated 1% NaCl solution

System	% Efficiency	Visual Observations
Control	—	Severe general corrosion
Polyurethane system I	81.3±3	severe blistering
Polyurethane system II	86.9±6	Few blistered spots
Epoxy system I	86.2±4	Moderately blistered
Epoxy system II	75.0±5	Coating removed fully
Powder epoxy III	87.9±0.6	Mild blistering
Powder epoxy IV	90.7±1.0	No blistering
CECRI cement slurry system	100	No blistering
Flame sprayed aluminium	100	No blistering

undergo blistering. Coal tar enriched polyurethane and polyamide epoxy systems suffered severe blistering.

Performance of various protective schemes with cost-benefit ratio is given Table 10. The durability factor for metallising (flame sprayed aluminium) is very high since it did not undergo any rusting. Durability factor

TABLE 10
Corrosion of Resistance of Different Protective Systems

Sl. No.	System	Thickness (W)	% area rusted	Durability factor (D) (D)	Cost/sq. m. Rs.	Cost Benefit Ratio (D/C)
1.	Flame sprayed aluminium coating	140	0*	—	183	Very high
2.	Powder epoxy system IV with greenish gray finish	200	0.442±0.031	227	350	0.646
3.	Powder epoxy system IV with greenish gray finish	250	0.476±0.02	210	369	0.569
4.	CECRI cement slurry coating system	200	11.86±0.37	8.43	6	0.234
5.	Powder epoxy system IV with greenish gray finish	150	2.495±0.41	40.0	331	0.121
6.	Powder epoxy system IV with greenish gray finish	75	3.31±0.12	30.21	322	0.094
7.	Coal tar enriched polyurethane system	68	16.88±5.10	5.917	71	0.083
8.	Polyamide epoxy system	144	14.09±5.40	7.13	90	0.08
9.	Powder epoxy system III with black glossy finish	200	3.78±0.49	26.45	350	0.076
10.	Powder epoxy system III with black glossy finish	75	5.581±1.01	26.45	350	0.076
11.	Powder epoxy system III with black glossy finish	150	6.16±2.02	16.20	331	0.05
12.	Powder epoxy system III with black glossy finish	250	9.61±3.40	10.41	369	0.028
13.	Aliphatic acrylic polyurethane system	100	68.8±7.6	1.453	65	0.022
14.	Control		100±0	1.0	—	—

*No rusting observed upto a period of 6 months

of other systems are in the range 1.45 to 227. Similarly cost-benefit ratio of flame sprayed aluminum is found to be very high and it is identified as the top performer. Cost-benefit ratio of other systems is in the range 0.02 to 0.646.

Powder epoxy system IV (with greenish grey finish) of thickness $200 \mu\text{m}$ is the second best system with a durability factor of 227 and a cost-benefit ratio of 0.646. Among the brushable systems, inhibited cement slurry system proves to be the best performer with high cost-benefit ratio. An advantage of cement slurry system is that even if there exists a defect, the galvanic current flow is negligible and corrosion is less (Rengaswamy, : 1991). In the case of organic coatings galvanic current from coated area (cathodic) to defect (anodic) is considerable which results in localised corrosion. Metallising (flame sprayed aluminum) if not applied perfectly can

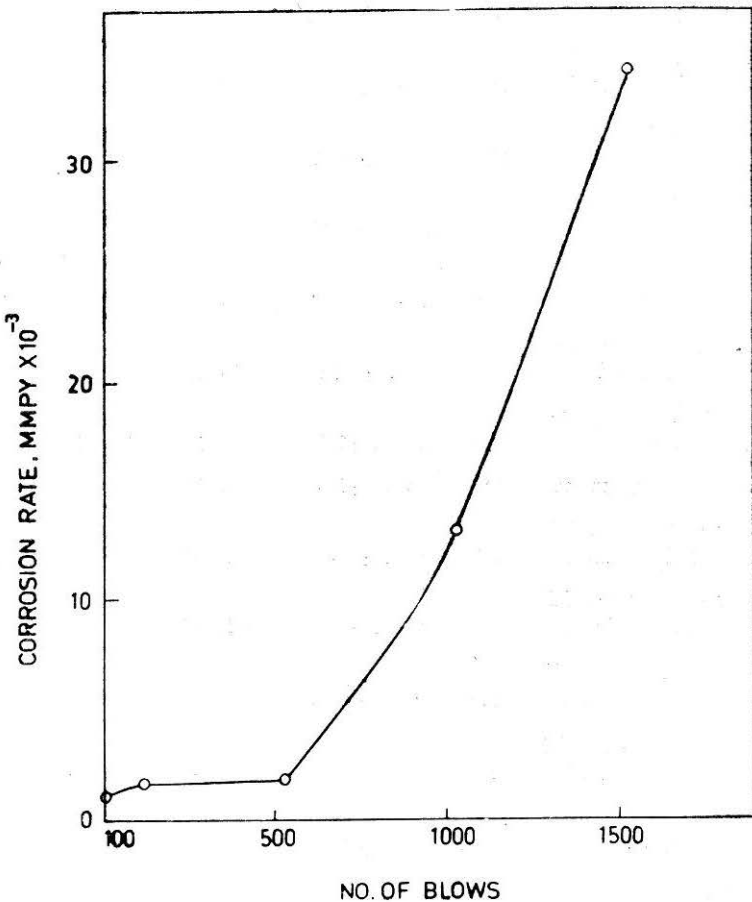


FIGURE 3 Corrosion Rate Vs No Of Blows For M40 Grade Concrete

TABLE 11

Efficiency of concrete Surface Coatings under Impact Blows (1500 blows)

System	Efficiency (%)
Solvent free Epoxy	95.8
Coal-tar enriched polyurethane	94.6
Aliphatic acrylic polyurethane	94.6
Polyamide epoxy system	89.3
Epoxy	57.3
Control	—

lead to enhanced cathodic reactions (hydrogen evolution) at the defect sites and entry of atomic hydrogen into steel.

Effect of Impact Blows

Corrosion rate of steel embedded in M40 grade concrete has been plotted against the number of blows imparted (Fig. 3). It is interesting to find that the corrosion rate increases very rapidly with the number of blows after initially remaining unaffected upto 500 blows. It may be due to continuous microcrack formation and its coalescence, under dynamically loaded conditions, leading to continuous crack pattern. In practice the piles are subjected to impact loading at the rate of 200 blows/metre (Ground Engg. : 1976). However this depends on height of fall, weight of hammer and soil strata encountered.

Different concrete surface coating systems behave different, manner (Table 11). Solvent free epoxy system is the top performer. Ordinary epoxy system does not offer much protection. Both coal-tar enriched and aliphatic acrylic polyurethane systems perform well with about 95% efficiency.

Conclusions

The following conclusions can be drawn based on the studies carried out :

1. Microalloyed HSLA steels have better corrosion resistance but are not cost-effective. Mild steel can be the cheapest splice material but a cost-effective and a durable protective system must be applied.
2. As a protective coating to mild steel splice, flame sprayed aluminum has been identified as the top performer by laboratory and field exposure studies. Among the brushable systems, cement slurry

system developed at CECRI has proved to be durable and cost-effective.

- Impact can significantly increase the corrosion of steel embedded in concrete. A solvent free epoxy system has been identified to efficiently protect concrete surface under impact blows.

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