Study on performance of waterborne anticorrosive coatings on steel rebars

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Abstract. Durability of reinforced cement concrete structures is mainly affected by corrosion of steel reinforcements. In order to protect the reinforcing bars from corrosion and to enhance the lifetime of reinforced cement concrete structural members, anticorrosive treatment to steel is of prime importance. Conventional coatings are solvent based. In this study, water based Latex was used to formulate anticorrosive coating. Latex is applied to steel specimen substrates such as plates and rods and their mechanical properties such as flexibility, abrasion, bendability, adhesive strength, impact resistance, etc. were studied. It was inferred that coating containing latex, micro silica, zinc phosphate, ferric oxide, aluminum oxide, titanium oxide and silica fume was found to possess more corrosion resistance under marine exposure conditions.

1. Introduction
Concrete is the most widely used construction material having very good compressive strength but very low tensile strength. To impart its tensile strength, steel reinforcements are normally provided in reinforced cement concrete (RCC). Reinforcing steel bars are normally well protected against corrosion by embedment in high-alkaline environment of concrete. Corrosion of embedded reinforcing steel in RCC construction is a world-wide problem affecting durability of concrete which can cause minor disfigurement to catastrophic collapse of the whole structure. Examples of corrosion of reinforcement include buildings and bridges which results in increased volume of steel, cracking, delamination and spalling of cover concrete. Also, structures under marine exposure are suffering severe damages due to penetration of chloride ions causing corrosion of reinforcing steel. When a small but uniform amount of moisture is present in the atmosphere, concrete will be carbonated to the depth of the steel reinforcement and the steel is likely to corrode uniformly. Alternatively, corrosion may occur at local points within the length of rebars, which may form severe notching or thinning whilst the remainder of the bar lengths is left un-corroded. Because of varying conditions that exist within structures, corrosion proceeds at different rates at different locations. In order to protect reinforcing steel form corrosion, universally adopted method is to provide anti-corrosive treatment to steel reinforcement before embedding in concrete. Different types of treatments used in practice are galvanizing zinc–aluminum coating, fusion bonded epoxy coating, cement polymer composite coating, epoxy phenolic rebar coating, epoxy-based coating, etc., majority of the conventional coatings are solvent borne. At normal temperature and pressure, these solvents emit volatile organic compounds (VOCs) and hazardous air pollutants (HAPs), which are dangerous and cause risk to human health. Most of the studies were conducted using solvent-based anticorrosive coatings. Various studies were carried out on corrosion-induced cracking of reinforced concrete and the performance of anticorrosive coatings.
Gao et al [1] conducted experimental and statistical studies on the effects of the load-induced cracks for predicting time needed for the initiation of corrosion and the critical time needed to maintain the integrity of the structure against failure. Gao et al [2] also conducted experimental studies under accelerated corrosion on reinforced concrete (RC) slabs and inferred that pre-cracked structure has noticeable influence on the corrosion damage under sustained loading. Authors [2] also conducted experimental studies on the loss of mass of reinforcing steel due to corrosion and the effect of inclusion of polypropylene fibers in concrete under accelerated corrosion. They observed that maximum mass loss of steel was occurred at the center of the corrosion region for the specimens corroded with pre-existing cracks. Also, addition of polypropylene was found effective in reducing the growth of crack speed without any reduction of the ultimate capacity of the specimen [3]. Subsequently, researchers [4] conducted statistical studies on the ranking of corrosion affected concrete bridges using multiple criteria decision making system. The same group of authors performed experimental and statistical studies on the effects of the load-induced cracks for predicting time needed for the initiation of corrosion and the critical time so as to maintain structural integrity [5].

Almusallam et al [6] conducted studies on the effectiveness of surface coatings in improving the durability of concrete and inferred that epoxy and polyurethane coatings perform better than acrylic, polymer and chlorinated rubber coatings. Cheng et al studied the effect of coatings to rebars on corrosion resistance and bond strength of reinforced concrete. They observed that the corrosion rate of zinc is higher than carbon steel in pH12 solution but lower in 3.5% NaCl solution. The bond strength decreases with an increase in corrosion rate for uncoated rebar and zinc-coated rebar. After 14 days accelerating corrosion process, the reduction ratio of bond strength for zinc-coated rebar is less than that of uncoated rebar [7].

Saravanan et al evaluated the performance of polyaniline pigmented epoxy coating for corrosion protection of steel in concrete environment. They stated that the corrosion resistance of polyaniline pigmented epoxy coating decreased initially and then increased due to a passivating ability of polyaniline pigment in electrochemical impedance study [8]. Baldissera et al carried out studies on performance of epoxy resin containing polyaniline for corrosion protection of mild steel bars. The corrosion behavior of coated mild steel samples was investigated in 3.5% NaCl solution by electrochemical impedance spectroscopy and concluded that coating containing SPAN was found to have the best performance in corrosion protection [9].

To the best knowledge of the authors, very limited studies were carried out using water as the solvent to disperse the resin for providing corrosion protection coating to reinforcing bars. There are certain specific advantages of using waterborne coating systems for corrosion protection of rebars such as reduced emission of volatile organic compounds and hazardous air pollutants, use of conventional application process, reduced toxicity and odor, good storage life, easy to clean, elimination of the problem of disposal of hazardous waste, etc. The objectives of this research work are: (i) to formulate various composition of water based anticorrosive coatings to steel rebars using latex as the binder and study their performance on abrasion, adhesion and impact resistance; and (ii) to identify the coating, which is the most suitable for corrosion protection of reinforcing steel under marine exposure.

2. Experimental studies

2.1. Materials and methods

2.1.1 Materials used. For undertaking this study, water roofing Latex purchased from Madurai was used as binders. Fly ash, ordinary Portland cement, feldspar, silica fume, china clay, kaolin, micro silica, clay were purchased in Madurai and used as fillers. Chemicals and minerals such as zinc phosphate (Zn₃(PO₄)₂), aluminum oxide (Al₂O₃), titanium dioxide (TiO₂), and ferric oxide (Fe₂O₃) were purchased from Hamada Company and utilized as inhibitors, hiding agent, and coloring agent, respectively.
2.1.2. **XRF analysis.** The chemical composition of the fillers, pigments and additives were determined using X-ray fluorescence spectrometry (XRF). The summary of XRF results of OPC, flash, feldspar, clay, kaolin, china clay, silica fume, micro silica, ferric oxide are presented in Table 1.

### Table 1. Chemical composition of materials used

| Material composition | OPC  | Fly ash | Micro silica | China clay | Kaolin  | Silica fume | Clay | Feldspar | Iron oxide |
|----------------------|------|---------|--------------|------------|---------|-------------|------|----------|------------|
| SiO₂                 | 6.514| 43.538  | 89.484       | 13.303     | 73.042  | 95.265      | 37.822| 49.464   | 2.829      |
| Fe₂O₃                | 11.157| 29.041  | 0.037        | 7.030      | 3.333   | 1.231       | 39.707| 1.085    | 94.98      |
| SO₃                  | 2.044| 1.179   | 1.371        | 0.874      | 1.524   | 3.193       | 1.522 | 1.472    | 0.646      |
| CaO                  | 78.754| 3.987   | 0.353        | 73.138     | 1.732   | 0.306       | 13.636| -        | -          |
| Al₂O₃                | -    | 10.501  | -            | 12.828     | -       | -           | -    | 1.360    | -          |
| Others               | 0.432| 7.472   | 7.298        | 4.369      | 5.764   | 5.402       | 46.66 | -        | -          |

2.1.3. **Preparation of surface of steel samples.** Steel plates of size 100mm x 150mm x 0.8mm, 100mm x 100mm x 0.8mm, 100mm x 75mm x 0.2mm, 100mm x 20mm x 0.8mm and steel reinforcing bars of 300mm length with varying diameters such as 8mm, 10mm and 16mm were used as samples, to which the formulated coatings were applied. Initially, the steel plates and rebars were cleaned using pickling solution and then washed twice in tap water, dried in desiccators and kept ready for coating. Figure 1 shows the collection of materials, cleaning, and drying in desiccators before applying the formulated coatings.

![Figure 1](image1.jpg)

**Figure 1.** Collection of materials (a), cleaning (b) and drying (c) process

2.1.4. **Formulation of latex coating systems.** In the present research, 18 coating composition systems using latex were formulated as given in figure 2. These coatings consist of waterproofing latex as the binder with various compositions of fillers, inhibitors, coloring agents, and hiding agents. After the surface preparation, the coatings were deposited on the specimen using the brush (in two layers). Figure 3 shows the composition of various latex-based coatings.
2.2. Experimental studies

Latex-based coatings are red in color, can be easily deposited, and have brushing consistency. All the above coatings were formulated and applied to the steel rods and substrates for evaluating the performance of coatings such as dry film thickness, bendability, hardness, flexibility, abrasion, film adhesive test, etc. All steel samples with 18 latex-based coatings were examined for their mechanical properties as per relevant ASTM standards.
2.2.1. Dry film thickness test. Dry film thickness test was conducted in accordance with ASTMD 1186, [10] using the instrument known as Elcometer. The surface coatings were applied on the steel plates of size 100mm x 100mm x 75mm. The coated plates were kept at 60°C in an oven for 3 hours. Using Elcometer, the thickness of coatings was measured in various 6 places on the plate both at front and back faces. The average value of thickness was taken as dry film thickness and the results are presented in table 2.

2.2.2. Hardness test. Resistance to indentation/scratching is termed as hardness. Film hardness measurement using pencil 6 B to 6 H (softer to harder) is a well-known inexpensive and rapid test. All the 18 latex-based coating steel plates were subjected to the pencil hardness as per ASTM D3363-05 [11] using 6B to 6 H by scribing at 45° angle to have a stroke of 6.5mm length. It was found that all the 18 types of latex-based coatings exhibited adequate resistance against scratching.

2.2.3. Bendability test. The steel substrate of size 100mm x 20mm x 0.8mm were coated with latex-based coatings and were dried for 48 hours at room temperature. Then they were bent to 90° and 180° as shown in figure 3. Then the substrates were inspected about the formation of crack or stress concentration area if any. In all the 18 types of latex-based coatings, no crack was found during both bending process.

2.2.4. Abrasion test. Latex-based coated dry steel plates of size100mm x 100mm x 0.8mm were coated with the 18 types of greener coatings. The initial weight of the coated plates was taken first. Then the plates were scribed with E4320 emery sheet and final weight after abrasion was taken. The loss in weight due to abrasion is shown in table 2.

2.2.5. Film adhesion test. Adhesive strength of coated film on the steel substrate was measured using tensometer. [12]. Tensometer is an electrically operated instrument and application of tensional force should be perpendicular to the coated surface of the specimen which is held vertically. The coating film adhesive strength of 18 latex coatings is given in table 2. It is evident from table 2 that LX17 coating gives better adhesion to the metal substrate compared to all other coatings. LX18 coating shows low adhesive strength.

2.2.6. Cracking resistance test. In accordance with ASTM D522 [13]. Steel plates were bent into conical shape using mandrel bend test equipment as shown in figure 4. The latex-coated steel plates were placed in the equipment so as to experience flexibility. In this test, the steel plates were bent in such a way that one end having 3mm diameter and gradually increasing to 38mm diameter at the other end within the length of 200mm. This is for determination of the resistance to cracking of attached green coatings on steel substrates. Latex-coated thin plates were placed in the equipment and were bent up to 180° in a single stroke. Formation of cracks (if any) was observed from 3mm die end
to the other end. It was observed that all coatings exhibited very good flexibility characteristics without any cracking.

**Table 2. Results of dry film thickness, abrasion and adhesive strength**

| Designation of coating | Dry film thickness (μm) | Initial weight | Abrasion test | Adhesive strength $^2$ (N/mm$^2$) |
|------------------------|-------------------------|----------------|--------------|---------------------------------|
| LX1                    | 93                      | 84.44          | 84.43        | 0.012                           | 8.16 |
| LX2                    | 109                     | 86.94          | 86.92        | 0.023                           | 7.72 |
| LX3                    | 135                     | 87.35          | 87.34        | 0.011                           | 8.17 |
| LX4                    | 165                     | 89.03          | 89.01        | 0.022                           | 8.94 |
| LX5                    | 97                      | 84.69          | 84.67        | 0.024                           | 8.02 |
| LX6                    | 95                      | 84.11          | 84.10        | 0.012                           | 8.10 |
| LX7                    | 88                      | 85.95          | 85.94        | 0.012                           | 8.13 |
| LX8                    | 89                      | 86.59          | 86.57        | 0.023                           | 7.83 |
| LX9                    | 103                     | 86.01          | 86.00        | 0.012                           | 7.91 |
| LX10                   | 121                     | 83.90          | 83.89        | 0.012                           | 7.69 |
| LX11                   | 152                     | 89.26          | 89.23        | 0.034                           | 8.21 |
| LX12                   | 127                     | 86.31          | 86.30        | 0.012                           | 7.96 |
| LX13                   | 95                      | 86.31          | 86.29        | 0.023                           | 8.21 |
| LX14                   | 99                      | 84.65          | 84.63        | 0.024                           | 7.81 |
| LX15                   | 85                      | 83.88          | 83.87        | 0.012                           | 7.92 |
| LX16                   | 93                      | 83.59          | 83.58        | 0.012                           | 7.63 |
| LX17                   | 134                     | 87.38          | 87.35        | 0.034                           | 8.98 |
| LX18                   | 99                      | 84.34          | 84.32        | 0.024                           | 7.62 |
2.2.7. Environmental exposure study. The rate of corrosion on coated surface area with and without diagonal scribes was determined by the environmental exposure study. For this study, one side surface of coated plate was scribed while the other side was left unscribed. All the edges of plates were dipped in wax so as to seal the edges from corrosion. All 18 coated specimens were exposed to a salty environment by spraying sodium chloride solution three times per day as shown in figure 5 for duration of 400 hours [14]. This was done to create severe environment (seashore) as shown in figure 6.

Table 3 represents rating specifications as per ASTM-D1654 [14]. Using carbide tipped pencil type scribing tool, the coated plates were scribed to obtain a uniform V-cut through the coating by holding the tool approximately at 45° angle to the surface. Cutting tool was positioned such that the carbide tip alone should be in contact with the surface. The creep value in was measured in millimeters and rating was given according to the recommendations of ASTM-D1654 [14]. The unscribed surface of the latex coating plates was also observed and percentage of failed area was noted. The comparative values are presented in table 4.

It can be seen from table 4 that LX4 and LX17 were having less creep at scribed surface and also less percentage of failure area on the unscribed surface, compared to other coatings. The comparative results are presented in figure 6.
Table 3. Rating specification as per ASTM-D1654

| Scribed plate creepage (mm) | Rating number | Unscribed plate Failed % | Rating number |
|-----------------------------|---------------|---------------------------|---------------|
| Zero                        | 10            | No fail                   | 10            |
| Over 0 to 0.5               | 9             | 0 to 1                    | 9             |
| Over 0.5 to 1               | 8             | 2 to 3                    | 8             |
| Over 1 to 2                 | 7             | 4 to 6                    | 7             |
| Over 2 to 3                 | 6             | 7 to 10                   | 6             |
| Over 3 to 5                 | 5             | 11 to 20                  | 5             |
| Over 5 to 7                 | 4             | 21 to 30                  | 4             |
| Over 7 to 10                | 3             | 31 to 40                  | 3             |
| Over 10 to 13               | 2             | 41 to 55                  | 2             |
| Over 13 to 16               | 1             | 56 to 75                  | 1             |
| Over 16 to more             | 0             | Over 75                   | 0             |

Table 4. Results on the rating number for environmental exposure test

| Designation of coating | Scribed plate | Coating ID | Unscribed plate Failed % | Rating number |
|------------------------|---------------|------------|---------------------------|---------------|
|                        | Creepage (mm) |            |                           |               |
| LX1                    | 3             | LX1        | 30                        | 4             |
| LX2                    | 3             | LX2        | 30                        | 4             |
| LX3                    | 2             | LX3        | 35                        | 3             |
| LX4                    | 1             | LX4        | 6                         | 7             |
| LX5                    | 3             | LX5        | 35                        | 3             |
| LX6                    | 4             | LX6        | 20                        | 5             |
| LX7                    | 6             | LX7        | 35                        | 3             |
| LX8                    | 4             | LX8        | 15                        | 5             |
| LX9                    | 4.5           | LX9        | 20                        | 5             |
| LX10                   | 6             | LX10       | 30                        | 4             |
| LX11                   | 3             | LX11       | 20                        | 5             |
| LX12                   | 2             | LX12       | 60                        | 1             |
| LX13                   | 3             | LX13       | 30                        | 4             |
| LX14                   | 2             | LX14       | 85                        | 0             |
| LX15                   | 2.5           | LX15       | 40                        | 3             |
| LX16                   | 3             | LX16       | 90                        | 0             |
| LX17                   | 0.5           | LX17       | 2                         | 8             |
| LX18                   | 2             | LX18       | 25                        | 4             |
2.2.8. Impact test: The resistance of latex-based coating against impact was determined as per ASTM D2794-93 [15] and the instrument is shown in figure 7. A standard weight of 1.8kg was dropped to strike an indenter which deforms the coating on the substrate and failure of a coating film was observed using the magnifier. Defected coating was marked as failed. It was observed that no cracking or loss of bond occurred at the impact area. All 18 types of coating passed the impact test.

Figure 7 (a) Impact test equipment                       (b) Impact test set up

3. Results and discussion
The formulated water borne latex coatings exhibited Dry film thickness ranging from 85 microns to 165 microns. Adhesive strength of coatings varied from 7.62 to 8.98 N/mm²; LX 4 coating and LX17 coating exhibited good adhesive strength. Regarding hardness test, all the 18 types of latex-based coatings exhibited adequate resistance against scratching. Also, all latex-based coatings were found to perform satisfactorily without the formation of any cracks or scratch under Bendability test. Environment exposure study of coatings revealed that LX4 (latex + micro silica + zinc phosphate + ferric oxide + aluminum oxide + titanium oxide+ silica fume) and lx17 (latex + ordinary Portland
cement + micro silica + zinc phosphate + ferric oxide + aluminum oxide + titanium oxide + silica fume) was found to have less creep at scribed surface and also less percentage of failure area on the unscribed surface. These coatings can be considered as the better coating.

4. Conclusions

The latex-based coating is a waterborne greener manufacturing eco-friendly coating. From the total 18 coatings, only two (namely, LX4 and LX17) exhibited a good corrosion resistance and were found to be the most effective by the performed environmental exposure experimental studies. To ascertain the durability of coatings, further corrosion evaluation studies, such as electro-chemical impedance, anodic polarization studies, Taber abrasion, automatic scratch test, and impressed voltage test have been carried out on the above coatings.

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[11] ASTM D3363-05 Standard test method for film hardness by pencil test.
[12] ASTM D2197-86 Standard test method for adhesion of organic coatings by scrape adhesion.
[13] ASTM D522-93a Standard test methods for mandrel bend test of attached organic coatings.
[14] ASTM D1654-08 Standard test method for evaluation of painted or coated specimens subjected to corrosive environments.
[15] ASTM D2794-93 Standard test method for resistance of organic coatings to the effects of rapid deformation (impact).