Condition Assessment of Induced Draught Cooling Towers Located In Different Climatic Regions of India

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Abstract
Induced Draft Cooling Towers (IDCT) are an important industrial structures, which removes the heat absorbed in the circulating cooling water systems of thermal power plants. The cooling tower in general comprises of RCC members’ viz. Column, Beam, Slab, Wall, Louvers, Fanstack Shell etc. The process of operation is itself an important factor which affects the durability of members of IDCTs, due to which the RCC members of IDCT are subjected to varying exposure condition, some members are continuous under water, some are partially submerged, some have alternate drying & wetting and some are completely dry. Due to different exposure conditions of RCC members of these structures generally shows very contrasting states of distress i.e. varying from apparently un-distressed to highly distressed state. Apart from process of operation of IDCTs, the other important factors that affect the durability of these RCC structures are presence of Chloride in water being cooled & Chloride in concrete present during the construction and carbonation due to aging of concrete. The RCC structures were assessed by various Non-Destructive evaluation techniques and deterioration mechanisms were established. The present paper highlights the findings of condition assessment studies of selected IDCTs located in different climatic regions of India.

Keywords: Condition assessment; Non Destructive Evaluation; Chloride; Carbonation

1. Introduction
Concrete infrastructure requires regular assessment in order to ensure safety and cost-effective maintenance practice. During the construction stage itself the placing, consolidation, and curing of concrete takes place in the field using labor that is relatively unskilled. Therefore the resulting product is highly variable by its very nature and construction method. Despite the above drawbacks, there has been progress in the development of nondestructive methods for testing concrete, and several methods have been standardized by the American Society for Testing and Materials (ASTM), the Canadian Standards Association (CSA), the International Standards Organization (ISO), the British Standards Institute (BSI), Bureau of India Standards (BIS) and others. The European standard for structural safety EN 1990 prescribes 50 years for buildings and 100 years for monumental building structures, bridges and other civil engineering structures. The structure interacts with the environment (both micro and macroclimate). To describe the environmental actions, it is necessary to describe them as surface temperature, humidity wetness and chloride conditions [1].

Durability assessments covers identifying the presence of internal voids or cracking, materials likely to cause disruptions of the concrete and the extent or risk of reinforcement corrosion. Carbonation depths, chloride concentrations, cover thicknesses, and surface zone resistivity and permeability will be key factors relating to corrosion. Electrochemical activity associated with corrosion can also be measured to assess levels of risk, using passive or perturbative test methods [2]. The ultrasonic pulse velocity method can be used for detecting internal cracking and other defects as well as changes in concrete such as deterioration due to aggressive chemical environment and freezing and thawing [3]. In the past, structural inspections of cooling towers have been employed as a tool for
assessing the condition of the shell at a particular point in time, deciding whether or not repair interventions are necessary, and selecting the most appropriate repair method [4]. Rebound hammer test, Pull-out and Pull-off tests, Ultrasonic pulse velocity (UPV) test, Core sampling and testing, Cover survey and Carbonation test are mostly used for the assessment of existing concrete structures [5,6].

It is important to note that almost all the NDT methods indirectly estimate the concrete strength and strength obtained by these methods, in most of the cases, is comparable. Even then, no single method can be said to be fully reliable and therefore, more than one method should be performed and results should be correlated 7. In order to have an optimal use of the structure and its stability and to achieve an adequate repair procedure, a thorough and logical investigation of distress causes was carried out in the current study.

2 Description of the Structure

Cooling towers are able to lower the water temperatures. Induced draft towers have large fans to force or draw air through circulated water. The water falls downwards over fill surfaces, which help increase the contact time between the water and the air - this helps maximize heat transfer. The structure is assembly of two or more individual cooling towers or ‘cells. The building of large cooling tower in general comprises of framed RCC structure having members’ viz. Column, Beam, Slab, Wall, Louvers, Fanstack Shell etc.

3 Method of Assessment

In order to investigate the performance of the cooling tower structure which is in a propagation phase of deterioration, an assessment of the current condition of the structure is necessary. This investigation is also necessary because of several other factors such as current maintenance, rehabilitation, serviceability conditions changes, investigation of structural stability and its function, and a study of current environmental conditions. Current state could include rapid assessment and visual inspection up to complex considerations which are taken into account in long time planning and performance.

The main purpose of visual surveying and investigation is the diagnosing of probable causes of any visual deterioration and ensuring that the structure remains in its integration and satisfactory conditions. The study had been carried out on 4 different cooling towers located at 4 different geographical locations of India. The details of IDCTs are as follows (Table-1)

Table-1
Details of Induced Draft Cooling Towers Investigated

| Description          | IDCT-1          | IDCT-2          | IDCT-3          | IDCT-4          |
|----------------------|-----------------|-----------------|-----------------|-----------------|
| Location             | Site-1 (Ratnagiri, MH) | Site-2 (Kanti BR) | Site-3 (Delhi) | Site-4 (Farakka WB) |
| Climate condition    | Tropical, Sea shore | Semi- arid | Semi- arid | Semi- arid |
| Exposure condition   | Very Severe | Severe | Severe | Severe |
| Year of Construction | 1999 | 1985 | 1997 | 1986 |
| Grade of Concrete    | M25 | M20 | M20 | M20 |
| Reinforcement        | Fe 415 | Fe 415 | Fe 415 | Fe 415 |
| Circulating water    | Sea Water | River water | River water | River water |
| Annual Average       | 75 | 65 | 54 | 61 |
| Relative Humidity    |               |               |                |                |
| Avg. Temp Min        | 21.1°C | 9.8°C | 7.6°C | 10.6°C |
| Max                  | 31.5°C | 37.2°C | 39.2°C | 36.8 °C |

The in-situ investigations are planned in such a way that both qualitative and quantitative evaluation of the mechanical and durability parameters of the reinforced concrete members of induced draught cooling towers (IDCT) can be assessed. The tests are as follows (Table-2).
Table-2
Details of Test Conducted for Condition Assessment of Induced Draught Cooling Towers

| Property under investigation | Test                              | Equipment type                          |
|-----------------------------|-----------------------------------|----------------------------------------|
| Concrete quality and durability | Ultrasonic pulse velocity, Concrete Cover | Electromechanical, Electromagnetic       |
| Concrete strength           | Cores                             | Mechanical                              |
| Corrosion of embedded steel | Half-cell potential, Resistivity, Carbonation depth, Chloride concentration | Electrochemical, Electrical, Chemical/Microscopic, Chemical/electrical |

4. Site Investigation

The paper presents comparative study on four Induced Draft Cooling Towers (IDCT) structures located in different regions across India. The brief results are as follows:

4.1 Visual Survey: The year of construction of IDCT of Site-1, Site-2, Site-3 & Site-4 were 1999, 1985, 1997 & 1986 respectively. During the visual inspection of the structures, majority of internal & external RCC members were in highly distressed condition in IDCT at Site-1. Majority of external RCC members were in highly distressed condition & few internal RCC members were in moderately distressed condition in IDCT at Site-2. Majority of external RCC members were in moderately distressed condition in IDCT at Site-3. Majority of external RCC members were in moderately distressed condition & majority of internal RCC members were in undistressed condition in IDCT at Site-4. In Site-1 sea water is being used and in Site-2, Site-3 & Site-4 the water is being sourced from rivers. The RCC members of IDCT at site-4 were coated by protective epoxy coating and at other three IDCT sites no protective coating was applied. The external RCC members are subjected to alternate drying & wetting which is severe exposure condition and internal members were continuously in exposure to water in all IDCTs. Cracks were observed at the construction joints in Fanstacks of all IDCTs. At Site-1 there are other 2 IDCTs on which protective coating was previously applied, distress found to be lesser comparing to IDCT under our study on which no protective coating is applied.

![Fig.1: Cooling Tower at Kanti](image1)

![Fig.2: Cooling Tower at Farakka](image2)

![Fig.3: Distress in IDCT at RGPPL](image3)

![Fig.4: Undistressed internal members of IDCT at Delhi](image4)

4.2 Assessment of Quality of Concrete by Ultrasonic Pulse Velocity Testing: The UPV results indicated the Quality of concrete is good to excellent in majority of RCC members of Site-2, Site-3 & Site-4. Quality of concrete is Medium in majority of RCC members in Site-1 (Table-3). This also indicates the extent of distress in terms of cracking/spalling of concrete which has occurred in different locations. Site-1 is exposed to very severe environmental condition without any protective coating and quality of concrete is also low, hence the distress is higher comparatively to other locations.
Table 3
Quality Grading of RCC Members of Induced Draught Cooling Towers

| Grading     | UPV Value Range | Site-1 (Ratnagiri, MH) | Site-2 (Kanti BR) | Site-3 (Delhi) | Site-4 (Farakka WB) |
|-------------|-----------------|------------------------|-------------------|----------------|--------------------|
| Doubtful    | < 3.0 km/s      | 27                     | -                 | -              | -                  |
| Medium      | 3.0-3.75 km/s   | 54                     | -                 | -              | -                  |
| Good        | 3.75-4.4 km/s   | 19                     | 71                | 86             | 100                |
| Excellent   | > 4.4 km/s      | -                      | 29                | 14             | -                  |

Fig. 5: Graphical Representation of Overall Quality of Concrete obtained by UPV Testing

Fig. 6: Photograph showing UPV Testing being done on beam of IDCT

4.3 Equivalent Cube Compressive Strength of Concrete by Core Extraction & Testing: The average equivalent cube compressive strength of concrete obtained by core extraction and testing was found to be M30 grade of concrete in IDCT-1 & IDCT-4 and M25 grade of concrete in IDCT-2 & IDCT-3.

4.4 Concrete Cover & Carbonation Depth Study: The average depth carbonation in all site locations was found to be lower than the provided average nominal covers Table-4.

Table 4
Average Nominal Concrete Cover & Average Carbonation Depth

| Parameter          | Site-1 (Ratnagiri, MH) | Site-2 (Kanti BR) | Site-3 (Delhi) | Site-4 (Farakka WB) |
|--------------------|------------------------|-------------------|----------------|---------------------|
| Nominal Cover      | 35                     | 37                | 39             | 39                  |
| Carbonation Depth  | 25                     | 19                | 6              | 5                   |

The exposure condition at Site-1 is Very Severe. At Site-2, 3 & 4, the exposure condition is moderate to severe. The nominal concrete cover assessed by electromagnetic cover meter at Site-1 was 35mm which is less than the required minimum 50mm for very severe exposure condition as per IS456: 2000 table no 16.
4.5 Half Cell Potential Test: The Half Cell Potential (HCP) values obtained from different locations indicated that there is a greater than 90% probability that reinforcing steel corrosion is occurring in that area at the time of measurement in all members of Site-1, in 38% members of Site-2 & 57% members of Site-3 (Table-5). In site-4 all members there is a greater than 90% probability that no reinforcing steel corrosion is occurring in that area at the time of measurement.

Table-5
Half Cell Potential measurements as per ASTM C876

| Range of Half Cell Potentials | Site-1 (Ratnagiri, MH) | Site-2 (Kanti BR) | Site-3 (Delhi) | Site-4 (Farakka WB) |
|------------------------------|------------------------|------------------|-----------------|---------------------|
| More positive than -200mV    | -                      | -                | -               | 100                 |
| Between -200mV to -350mV     | -                      | 62               | 43              | -                   |
| More negative than -350mV    | 100                    | 38               | 57              | -                   |

Comparing to other site locations the potential values are more negative as obtained at Site-1, which indicates the distress is higher in this structure. The potentials values are more positive in Site-4 which indicates that the distress is less.
4.6 Chemical Analysis of Concrete Powder samples: The acid soluble chloride content is found to be high in Site-1 & Site-3 (Table-6). In Site-2 & Site-4 the chloride content is acceptable.

Table-6
Chemical Analysis of Concrete Powder Samples

| Region          | Layer Depth (mm) w.r.t. outer surface of RCC member | Average Value (kg/m³) |
|-----------------|----------------------------------------------------|-----------------------|
|                 |                                                    | Site-1 (Ratnagiri MH) | Site-2 (Kanti BR) | Site-3 (Delhi) | Site-4 (Farakka, WB) |
| Within Cover Region | 0-20                                             | 2.04                  | 0.7               | 6.00          | 0.15              |
|                  | 20-30                                             | 1.01                  | 0.6               | 6.36          | 0.14              |
| Beyond Cover Region | 40-60                                            | 0.49                  | 0.8               | 5.70          | 0.14              |

4.7 Chemical Analysis of Water Sampled from Cooling Tower Sites: The test result of water sample collected from site-1 (Table-7) which is located at sea coast have higher Sulphate Content, Chloride Content, Inorganic Matter & Organic matter than the other locations. The higher chloride content in obtained in concrete which is clearly due to ingress from external source i.e. sea water being used and no protective coating is applied which made RCC members more susceptible to chloride ingress. At Site-3 also the Chloride ingress occurred from the water being used and no protective coating was applied on RCC members.

Table-7
Chemical Analysis of Water Samples from Cooling Tower Site

| Sl. No. | Content       | Permissible limit as per IS :456-2000 | Site-1 (Ratnagiri, MH) | Site-2 (Kanti BR) | Site-3 (Delhi) | Site-4 (Farakka WB) |
|---------|---------------|--------------------------------------|------------------------|-------------------|----------------|---------------------|
| 1       | pH            | Not less than 6                      | 8.41                   | 7                 | 6.9            | 8.55                |
| 2       | Sulphate (SO₃)| Max. 400 mg/l                        | 2421 mg/l              | 640 mg/l          | 321 mg/l       | 188 mg/l            |
| 3       | Chloride (Cl) | Max. 500 mg/l                        | 23750 mg/l             | 131 mg/l          | 847 mg/l       | 33 mg/l             |
| 4       | Inorganic Matter | Max. 3000 mg/l                  | 36900 mg/l             | 1343 mg/l         | 1125 mg/l      | 397 mg/l            |
| 5       | Organic Matter | Max. 200 mg/l                       | 2318 mg/l              | 56 mg/l           | 89 mg/l        | 52 mg/l             |
| 6       | Suspended Matter | Max. 2000 mg/l                  | 12 mg/l                | 79 mg/l           | 48 mg/l        | 50 mg/l             |

5. Findings of Investigation

The distress has occurred due to corrosion of embedded steel reinforcement, which has caused cracking and spalling of concrete. Based upon the various NDE test results it is found that the distress has occurred in mostly external RCC members which are in severe exposure condition and not provided with any protective coating. The IDCT which is provided with protective coating performed better than the IDCTs which are not provided with any protective coating. At Site-1, overall Quality of Concrete was varying from Doubtful to Good. Strength of Concrete was satisfactory. Average concrete cover is less than the required minimum for very severe category of exposure. No protective coating was provided. At Site-2 & 3, overall Quality of Concrete was varying from Good to Excellent. Strength of Concrete was satisfactory. Average concrete cover is more than the required minimum for moderate category of exposure. No protective coating was provided. At Site-4, the overall Quality of Concrete was Excellent. Strength of Concrete was satisfactory. Average concrete cover is more than the required minimum for moderate category of exposure. Protective coating was provided. Although the nominal concrete cover assessed at all locations is less than the required to meet durability requirements, the carbonation depth is within cover region in all the tested site locations. This indicates that presently there is minimal chance of carbonation induced corrosion, except at locations where cover is relatively low. The distress specifically in Site-1 & Site-3 has occurred due to chloride induced corrosion of embedded steel reinforcement. In this case high chlorides content present in the cooling water have ingress into the concrete cover, which is clearly shown by chemical analysis results since chloride levels are found to be higher in outer layers than the inner layers of RCC members.

Due the extensive corrosion of reinforcement & spalling of concrete, the IDCT-1 was not recommended to be repaired as the same will not be economically feasible. IDCT-2 & IDCT-3 which have moderate distress, it was recommended to carry out major repair work by indigenously available materials. IDCT-4 was having least distress therefore it was
recommended for minor repair work. For IDCT-4 where distress was least, it was recommended to repeat the application of protective coating every five years.

6. Conclusion

The equivalent cube compressive strength obtained by concrete core testing indicates that the strength values are satisfactory for required grade of concrete in all IDCTs. The UPV test results indicate the overall quality of concrete in Site-2, Site-3 & Site-4 was good to excellent and in Site-1 the some RCC members with doubtful quality were present. The depth of carbonation was found to be within the cover region in all IDCT structures. The number of RCC members having more than 90% probability of corrosion in embedded steel was higher in of Site-1 than in rest of the sites. The chemical analysis results indicates that the clear ingress of chlorides from circulating water into the concrete members at Site-1 & Site-3. Based up on various NDT test results it can be concluded that the distress in the IDCT structures has occurred mostly due to severe category of exposure condition i.e. alternate drying and wetting in the external RCC members, except the structure which was provided with protective coatings. At Site-1(Ratnagiri) & Site-3 (Delhi) distress has occurred due to Chloride induced corrosion. At Site-2 (Kanti, Bihar) minor distress has occurred at few locations due to carbonation induced corrosion only where concrete cover is relatively low. At Site-4 (Farakka) majority of members are undistressed since the protective coating is applied at this structure.

The IDCTs which are located in coastal region are subject to very severe environmental condition as well as have higher susceptibility for chloride ingress. The IDCT which is provided with protective coating performed better than the IDCTs which are not provided with any protective coating.

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