Design considerations and maintenance of concrete mill structures

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The factors affecting the performance of concrete mill structures are discussed, with particular attention to chemical and chloride ion attack, concrete mix design and admixtures, selection of coatings and other protective systems, detailing of reinforcing bars, construction quality control, and maintenance.

In the past, concrete structures have performed in a mixed fashion. Some structures have required almost no maintenance and repair, while others have suffered extreme deterioration requiring expensive repairs. This paper is intended to provide an overview of the practical means of extending the useful life of concrete structures through proper design, construction, and maintenance.

Concrete structures will perform well in a pulp and paper mill environment if the engineer, the contractor, and the owner each do their part. The structural engineer must not only understand the loads to which the structure will be subjected but also the level of exposure to adverse environmental conditions. Pulp and paper mill environments often demand more attention to design and detailing provisions than found in current building codes. These considerations must be reflected in design drawings and specifications. The contractor must understand and follow the design drawings and specifications using good construction practices. The owner must be willing to pay for the appropriate construction materials and techniques. After the structure is in service, it must be maintained in a timely manner.

Concrete structures deteriorate in two principal ways: dissolving or deterioration of the cement paste which binds the aggregate particles together; and the corrosion of steel reinforcement or steel embedments, resulting in spalling of the concrete. In general, the cement paste will not withstand sulfates, acids, or high concentrations of carbon dioxide, necessitating an effective surface seal to exclude the contaminant. Corrosion of reinforcing bars is primarily an electrochemical process caused by salts containing chlorides and carbon dioxide and influenced by other external environmental conditions such as wetting and drying, oxygen, chemical attack, and temperature. Chloride ions disrupt the naturally forming protective film (iron oxide) between the concrete and steel. Carbon dioxide causes carbonation of the concrete, which reduces the alkalinity of the cement paste and the effectiveness of the naturally forming protective layer. These mechanisms allow the formation of corrosion cells, the basis of electrochemical corrosion.

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Planning and design considerations

Planning

During the project planning stage, identification of adverse exposures should be determined and the appropriate materials and structural systems selected. As an example, many precast elements have not performed as expected, primarily because they were detailed as standard building products and did not have adequate concrete encasement (called cover) to protect the reinforcement from corrosion. In most instances, these standard elements would have performed satisfactorily if the reinforcement had adequate cover and if the concrete mix had been designed for lower permeability.

Concrete mix

Durability, not compressive strength, is the most important criterion for the concrete in a mill structure.

Cement and water form a paste that coats and bonds the aggregates together to form a solid body as the paste hardens. In simple terms, it is the glue that holds concrete together. The quality of this paste directly affects the concrete strength and durability. Too much water will result in a weaker paste, lowering the strength, adversely affecting the durability, and increasing the permeability.

One of the most important considerations in reducing corrosion of reinforcing bars is to proportion the concrete mix for low permeability and low shrinkage. Low permeability reduces the rate at which contaminants such as corrosion-causing chloride ions penetrate concrete.

Restricting the water-cement ratio to 0.4 or less by weight is the most important step in accomplishing this. Admixtures may contain water which should be accounted for in determining the water-cement ratio. Lower shrinkage should reduce the amount of cracking, decreasing the number of locations where contaminants can penetrate.

Reducing the water-cement ratio to the level discussed above may require the addition of an admixture to improve concrete workability. These chemicals act as dispersants, forcing cement particles apart and allowing water trapped by the cement particles to escape. Normal-range water reducers allow about a 10% water reduction. High-range water reducers (also called superplasticizers) permit an even larger reduction of water content, up to about 20%. In addition, superplasticizers can be used without a corresponding reduction in water content to give a concrete mix with a very high slump, 200–250 mm (8–10 in.), that does not lose strength or segregate during placing. Typical doses of superplasticizer are 3–12 ml per kilogram of cement (5–18 oz per 100 lb of cement). Superplasticizers have a limited life of 30–45 min, so it is important to have the ability to add them at the job site if the concrete cannot be delivered in a short period of time.

Although limiting the water-cement ratio is the most important mix consideration, other beneficial measures include:

- Specifying a minimum cement content regardless of strength requirements. Usually the minimum cement content should be at least 300 kg/m³ (5.5 sacks per cubic yard) for 28 MPa (4000 psi) concrete and 360 kg/m³ (6.5 sacks per cubic yard) for 35 MPa (5000 psi) concrete. Exact proportions should be established depending upon aggregate sources, aggregate size, and other local conditions.
- Using Type II, or Type I–II cement (Type I cement meeting the chemical requirements of Type II). These types of cement are preferred because of their moderate sulfate resistance and because they produce less heat during curing, which often results in less shrinkage and cracking.
- The addition of pozzolans, such as fly ash, results in a denser, less permeable concrete. They also may be used to reduce the amount of cement; however, the cement content should not be reduced below the minimum described above. Fly ash with a maximum 1% loss on ignition should be specified to maintain the effectiveness of air entrainment admixtures. Pozzolans also improve concrete workability, and when substituted for some cement, may produce a cooler mix, resulting in less cracking. Pozzolans in the presence of portland cement will themselves provide cementing action. Typically, up to 15% of the cement may be replaced with fly ash as long as the minimum cement content described above is maintained and not more than 120 lb of fly ash/yd³ of concrete is used.
- The addition of silica fume, very fine silica particles, produces results similar to fly ash, with the added benefits of increasing strength and significantly decreasing the electrical conductance of the concrete. The increased density and decreased conductance help to reduce the potential for reinforcing bar corrosion due to electrochemical action. Silica fume should have a minimum silicon dioxide content of 90%, with the remaining 10% made up of trace elements. A typical dosage rate is 7.5% silica fume by weight of cement.
- Calcium nitrite is an admixture that is added to concrete to stabilize the natural passivating iron oxide layer on the reinforcing bars. The use of this admixture requires determining the chloride loading that will eventually reach the reinforcing bars over the life of the concrete member. The amount of calcium nitrite required to meet the loading is then determined and added to the concrete mix. The effectiveness of this admixture can be eventually used up by chlorides if the chloride loading level is underestimated.
- Air entrainment in concrete involves the use of an admixture to entrain microscopic air bubbles in the concrete mix. Benefits of air entrainment include improved durability when subjected to moisture during freeze-thaw cycles (the air bubbles relieve the expansive force of water in the concrete), improved workability, and reduced bleeding. Air entrainment is recommended for concrete subjected to water and freeze-thaw action. As a guideline, specifying 5% air entrainment with a tolerance of ±1% in the mix should cover most situations. Too much air, 10% or more, will cause a loss of strength and adversely affect finishing. The use of air entrainment will result in a less dense concrete that is somewhat less resistant to chemical attack, but elimination of air entrainment should only be considered if there is no danger of freeze-thaw action.

The admixtures discussed above are commonly used to increase concrete durability. However, there are many other admixtures that can be used to improve or modify the behavior of concrete. Admixtures containing calcium chloride should be avoided so that the initial chloride loading of the concrete will be at its lowest possible level.

Structural design

Serviceability, not strength, often controls the design of concrete members in a mill structure. In this case, serviceability means the resistance the concrete structure has to forming large cracks under applied loads. Harsh pulp and paper mill environments necessitate designing and detailing for smaller crack widths than would normally be allowed by current building codes. In general, crack widths less than 0.2–0.25 mm (0.008–0.01 in.) should not affect concrete durability.

The depth of concrete cover over reinforcing bars is another important parameter in controlling corrosion. Minimum clear cover should range from 50 mm to 58 mm (2–2.25 in.) with the lower value for concrete with 20 mm (0.75 in.) and smaller aggregates. Again, this recommendation exceeds that required by current building codes. These values include an allowance for normal tolerances in placing reinforcing bars.

Consideration must be given to the proper location of structural joints to allow for the relief of internal concrete stresses. Internal stresses occur from concrete shrinkage, temperature changes, changes in moisture level within the concrete, time variations between concrete pours, and many other reasons. If not properly accounted for, these stresses can result in eventual cracking of the structure

and may precipitate corrosion. Joints can be placed in locations to control these stresses and minimize random cracking. Joint locations could include walls, floor slabs, or a complete vertical joint through the structure.

Sealers and coatings

Coating systems are available for protection of concrete mill structures from chemical attack. Solvent-borne coatings are particularly useful as sealers and surface penetrants, while solventless (100% solids) coatings are useful for a wider range of chemical attack resistance. Careful selection of these materials is required in high temperature areas. Since they are coating systems, periodic maintenance should be performed for optimum performance. Epoxy coatings should be applied only to hardened concrete and may not be advisable where concrete has already been permeated by chlorides or other chemicals.

Silanes are protective sealers used to resist chlorides and react chemically to form an outer layer on the concrete that is repellent to liquid water but permeable to water vapor. These sealers offer good, long lasting protection on concrete surfaces that are not subjected to abrasion, on such areas as exposed beams, columns, and the undersides of slabs. Silanes may be covered with coatings such as methacrylate for additional protection against chlorides as well as airborne contaminants.

Reinforcement coatings and noncorrosive reinforcement materials

Epoxy coatings offer additional protection to reinforcing bars against chloride-induced corrosion, especially if the quality control during concrete placing is poor or if the concrete cover is inadequate. Fusion-bonded coatings are superior to painted coatings. Epoxy-coated steel reinforcement should not be used in locations where the concrete will be subjected to temperatures above 65°C (150°F). Care must be taken with handling the bars, and field repairs to the coatings are often necessary when damage occurs. Also, development lengths and splice lengths for epoxy coated bars should be increased above current building code requirements.

Stainless steel reinforcing bars are currently available in all common bar sizes. These bars have an allowable yield stress of 420 MPa (60 ksi), which is the same strength as regular steel reinforcing bars. However, cost is an important factor, since stainless steel bars cost approximately six to eight times as much as regular bars.

Standard reinforcing bars can be galvanized for corrosion protection. If galvanizing is used, then all reinforcing should be galvanized. Tests have shown that galvanizing only the outer surface or top layer bars in slabs leads to increased corrosion rates in the black or uncoated bars.

Fiberglass reinforcing bars also can be used as a replacement for steel bars in some situations. However, the fiberglass materials and manufacturing methods must be suitable for the alkalinity of concrete, or degradation will occur.

Fibrillated polypropylene fibers also are available for use as secondary reinforcement in concrete structures. They are not intended to replace reinforcing bars. These fibers are added to the concrete during mixing, resulting in uniform distribution in the concrete. They will not react with chlorides and should not degrade, rust, or corrode. They help to reduce concrete shrinkage in the plastic and hardened states and hold cracks together, resulting in concrete that is more durable and less permeable.

Construction

Following good construction practices and understanding the contract documents are vital links in building a durable concrete structure. No matter how well the structure is designed or how many of the durability provisions discussed above are incorporated in the contract documents, the construction period is the time when the success or failure of the structure is achieved.

A preconstruction conference is an excellent forum to explain to the contractor and concrete supplier the special provisions included in the concrete mix design and to review critical areas and procedures for placing, testing, finishing, and curing. It is extremely important to have these matters worked out well in advance of the arrival of the first ready-mix truck.

As discussed previously, it is very important to control the amount of water in concrete to achieve a high quality material that will be durable. Contractors typically like to add water to the concrete to make it easier to place in the forms and will argue that this is acceptable since cylinder strengths will meet or exceed the concrete strength specified. However, if water is added, the water-cement ratio will increase and the durability of the concrete will be compromised, leading to premature deterioration.

Reinforcing bar placement should be checked to ensure that the bars have been installed in accordance with the design drawings and that the specified cover of concrete will be achieved. A decrease in cover will decrease the durability of the structure.

Placement and consolidation of the concrete must also be monitored to ensure that the concrete is placed uniformly to avoid segregation of the constituents and vibrated adequately to obtain the desired density of the material.

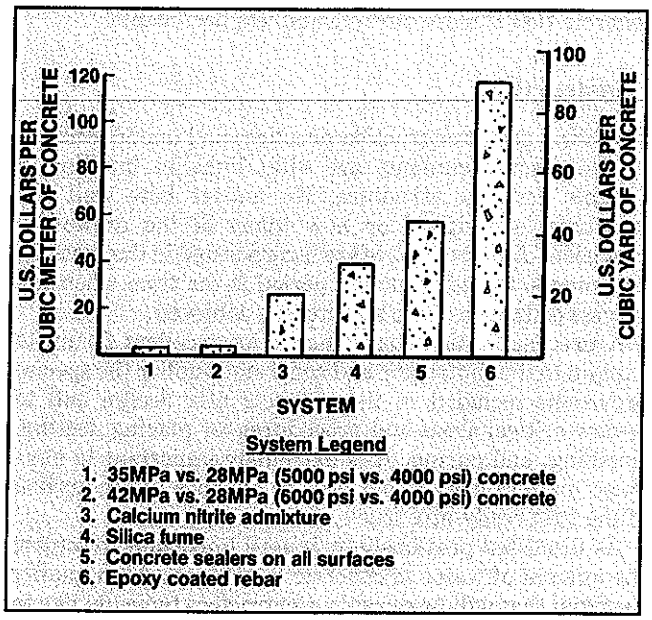
Finally, the concrete must be adequately cured to ensure that it gains its design strength, to avoid microcracking due to rapid curing, and to minimize shrinkage.

Maintenance

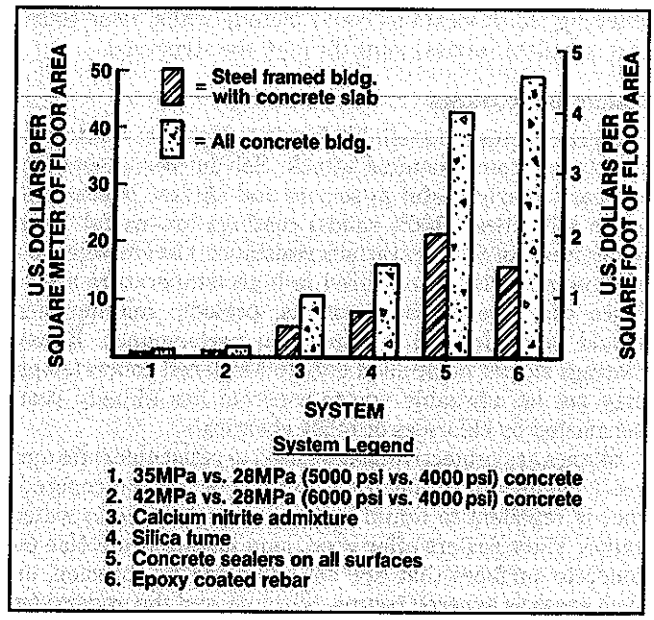
One of the most important ways to maintain a structure is to observe damage during its earliest stages and then to take appropriate corrective action. Too often the structure is ignored until the damage is substantial and concern develops that a failure is imminent. Once they are confronted with the possibility of a failure, users of the structure often implement a quick fix without determining the real cause of the problem. When damage is observed, it is extremely important to identify its extent and understand its cause. Too many repairs are made without accounting for and correcting the cause of the damage, leading to the eventual failure of the repair.

It is important that knowledgeable personnel trained in repair of concrete structures supervise the repair. Even then, some repairs may never be completely satisfactory due to the complex nature of both the cause and repair.

1. Concrete protection cost per unit volume



2. Protection cost per unit area



Comparative costs

In order to optimize concrete design in mill structures, many factors must be considered to make the proper decision on reinforcing bar protection. Costs of various protection systems will vary widely with respect to how concrete is being utilized. For example, an all-concrete structure will have markedly different costs for various reinforcing bar protection systems than a steel framed structure with only concrete floor slabs. The estimated costs of protection systems, expressed in relation to concrete volume, are shown in **Fig. 1.**

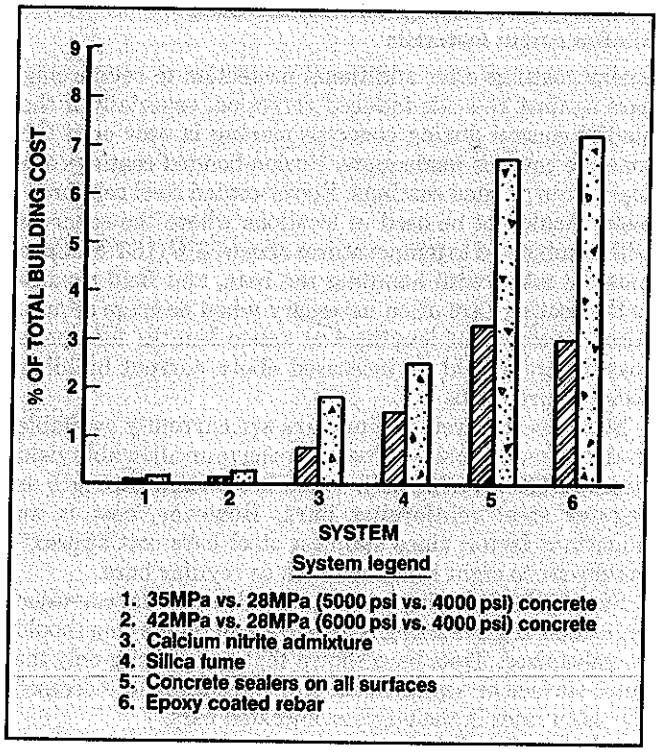
Figure 2 illustrates the cost of the same protection systems expressed in relation to floor area. It is interesting to note the reversal of relative costs between sealers and epoxy coated reinforcing steel when used in all-concrete structures versus a steel framed structure with only a concrete slab. The reason for this is that slabs on steel framing have a greater relative surface area and a lesser amount of reinforcing bars per unit volume of concrete than the beams and columns of an all-concrete building.

Figure 3 shows the additional cost of providing the protection systems expressed as a percent of total building cost for both all-concrete structures and steel framed structures with concrete slabs. The costs vary between 0.1% to 7%, depending upon the protection system and the type of structure.

Increasing concrete strengths to obtain a more durable, denser mix has the lowest cost—less than 0.1% of the total building cost. Part of the increased cost for the concrete is offset by reduced reinforcing bar cost resulting from shorter lap lengths, less shear reinforcement, and possibly reduced member sizes.

All the costs stated on the figures are in U.S. dollars and are based on pricing for the summer of 1989. The relative costs of the protection systems and their estimated costs may not be accurate in locations outside the U.S., depending upon availability of materials and construction practices. In addition, variations in building structures may cause some variations in the percentages shown in Fig. 3.

3. Protection cost as a percent of total building cost



Conclusion

The three most important considerations in specifying, designing, and constructing concrete mill structures are to specify a dense, high quality concrete using suitable

materials and a low water-cement ratio; to provide additional concrete cover over reinforcing bars; and to properly place, consolidate, and cure the concrete. The cost of doing these three things is insignificant compared to the cost savings in future maintenance. It is estimated to be less than 0.1% of the total building cost.

Additional protection is available through the use of admixtures, sealants and coatings, and special reinforcing bars and coatings. These more expensive materials may be justified when considering life cycle costs, where concrete is exposed to a harsh environment.

Periodic inspection, early detection of damage and accurate assessment of its cause, and selection of correct repair materials and procedures are the keys to proper maintenance and reduced maintenance costs for concrete structures.□

Literature cited

1. American Concrete Institute, ACI 318-83, Building Code Requirements for Reinforced Concrete, November 1983.
2. American Concrete Institute, ACI 318R-83, Commentary on Building Code Requirements for Reinforced Concrete, November 1983.
3. American Concrete Institute Committee 350, ACI 350R-83, Concrete Sanitary Engineering Structures.
4. American Concrete Institute, Publication No. SCM-13, Back to Basics Repair of Concrete, 1986.
5. American Concrete Institute, Publication No. SP-49, Corrosion of Metals in Concrete, 1978.
6. American Society for Testing and Materials, Publication No. STP 629, Chloride Corrosion of Steel in Concrete, 1977.
7. Berke, N. S., Pfiefer, D. W., and Weil, T. G., Concrete International, Protection Against Chloride-Induced Corrosion, 10(12): 45(1988).
8. Dale, E. J., The Construction Specifier, Eliminating Concrete Problems, 35(4): 39(1982).
9. Klein, F., Hoffman, E. S., and Rice, P. F., Concrete International, Application of Strength Design Methods to Sanitary Engineering Structures, 3(4): 35(1981).
10. Mather, B., The Construction Specifier, How to Make Durable Concrete, 42(1): 48(1980).
11. National Association of Corrosion Engineers, Solving Rebar Problems in Concrete, 1982.
12. National Cooperative Highway Research Program, Report No. 244, Concrete Sealers for Protection of Bridge Structures, 1981.
13. Portland Cement Association, Building Movement and Joints, 1st edn., EB086.01B, 1982.
14. Portland Cement Association, Design and Control of Concrete Mixes, 13th edn., EB001.13T, 1988.

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