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Application of Non-destructive Testing (NDT) Techniques on Reinforced Concrete Structure: A Review

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Abstract: To properly maintain our public infrastructure, engineers and designers must learn different methods of inspection. An exhaustive review has been carried out for different aspects of non- destructive testing (NDT) adopted for RCC structures. NDT evaluates the remaining operation life of different components of structure. It provides an accurate diagnosis which allows prediction of extended life operation beyond the designed life. Different aspects are considered which includes condition assessment, durability, corrosion, condition ranking and service life of structures. In this review, several non-destructive inspection methods are evaluated, with the aim of identifying those, which are practical for detecting defects at early in the production sequence as possible. The methods used for carrying out non destructive analysis used by different investigators are also discussed. Merits and demerits of each method are also stated. RCC structures considered are reinforced buildings, bridges, ESRs, recently developed NDT techniques which are useful for prediction of performance of structure are also included.
Keywords: Corrosion, Durability, NDT, Serviceability, Water Tanks

I. INTRODUCTION

Nondestructive testing (NDT) is employed as a non-invasive indirect testing technique for the condition assessment of structures and its component. NDT methods are based on the interaction of controlled physical ‘‘disturbances” with the internal structure of the test object. Condition assessment of a structure is of prime importance before any repair or maintenance operations is carried out. This assessment is necessary for efficient repair strategies and appropriate allocation of funds for the project. There have been projects in which the required repair was much more extensive than expected and the repair costs exceeded the replacement cost of the whole structure because the internal damage was not discovered until the commencement of repair. Reliable information of the existing condition of a structure, is possible only through an NDT survey using well-established methods. Furthermore many NDT methods are employed for quality control during or soon after the construction operations.

II. DEFECTS IN CONCRETE

Concrete is a composite material that can be produced from numerous mix proportions using its constituent ingredients with the varied end product properties. Concrete can undergo deterioration because of durability issues in the short term and long term. Failure of addressing these can seriously effect the intended use of the concrete element and, in many cases, the overall integrity of the structural system.

A. Delamination

Delamination defects are most common in bridge decks and other plate like reinforced concrete structures. Published reports reveal that corrosion affected reinforced concrete structures are generally prone to delamination and cracking. This type of defect is subsurface crack parallel to a surface and in most cases is not noticeable given its location. Unchecked progression of delamination may ultimately result in loss of structural serviceability and may cause premature failure of reinforced concrete elements.

B. Cracks

Cracks in concrete elements may result due to loading, volume change and several durability issues like freeze-thaw induced cracking and chemical attack. The cracks provide a direct path for the invasive materials to get inside the concrete and further the deterioration. The extent and size of the crack is hence an important parameter in condition assessment practices.

C. Debonding

The provision of bonded concrete overlay on pavements and bridge decks is a major rehabilitation technique for these structural elements. The bond between the overlay and the existing slab is to ensure monolithic behavior. The loss of bond strength, termed as debonding of overlay, due to various reasons is a major durability issue in the rehabilitated concrete element.

D. Voids and Honeycombing

Both voids and honeycombing are primarily due to poor quality control during construction. Honeycombing is a disproportionately high localized void ratio mainly due to inadequate consolidation of concrete.

E. Loss of Ground Support

This is not a concrete defect per se, rather it is more of geotechnical induced failure. Due to geotechnical issues, concrete pavements and tunnel linings may lose the adjacent ground support, which affects the integrity of the concrete structure. The primary structural distress in continuously reinforced concrete pavements is the edge punchout. It is caused primarily by loss of support beneath the pavement. The loss of soil support around tunnel linings can result in circumferential cracking due to differential settlement or longitudinal cracking due to ovalization

III. DURABILITY

For life safety reasons, current building codes have largely focussed on design for structural capacity and serviceability, but many do not adequately address durability design. It should be noted that concrete requirements for durability are typically more stringent than those required for structural capacity, and structural designers become concerned with the additional costs of what many consider to be "overdesign." In their defense, it must be noted that the majority of the structural elements in buildings are not normally exposed to severe environments.

If current codes are followed, then structural failures are rare, but numerous other structures, or segments of structures in different icroclimates, have prematurely deteriorated in severe environmental exposures, resulting in costly repairs or replacement due to inadequate code requirements for the assigned exposures. This is not just in terms of the specified concrete materials and mix designs, but also lack of consideration in construction specifications or inadequate inspection for issues including avoidance or mitigation of alkali-aggregate reactions, minimization of non-structural cracks (due to restrained thermal and drying shrinkage), provision and inspection of adequate clear rebar cover, provision of adequate curing for durability in the intended exposure, slopes and drainage that are insufficient to adequately account for long-term settlement or creep.

For structures in severe exposures, codes and specifications need to be developed that far more comprehensive in terms of both durability design and in execution of durable concrete construction. For example, the minimum curing requirements in most standards are only based on meeting a certain fraction of the specified strength and not on that needed to obtain a specific level of resistance to fluid ingress in the cover layer protecting the reinforcement. As well, they should also include adoption of performance-based test methods that directly relate to durability, but recognizing that new and better test methods are also needed as existing ones do not adequately cover all of the potential mechanisms of deterioration nor necessarily relate well to field performance.

When the testing is to be carried out on the concrete structures, In many specifications, testing requirements are often limited to slump or slump flow and air content of fresh concrete and strength of hardened concrete. The inclusion of performance test requirements as options for the various durability exposures would allow acceptance of mixtures with equivalent performance to the current prescriptive requirements in many standards. Some discussion about what and where to test is warranted.

Tests are or can be performed at various stages in construction.

1) *Pre-qualification Tests:* Used by producers to demonstrate that a concrete mixture, when placed and cured under defined conditions, can meet the specification requirements and, if needed, provide input data for service life prediction. These tests often require significant lead time to complete and may include tests needed as inputs to service life models.
2) *Identity Tests:* Performed when the concrete arrives on-site but before concrete is placed to demonstrate that the concrete being supplied is equivalent to the mixture that was pre-qualified. Unfortunately the ranges of identity tests that can be performed prior to acceptance of the truck load of concrete are quite limited. Typically, slump or slump flow is measured, and air content is determined. Useful information on concrete uniformity and air content can also be obtained from measuring the fresh density of the concrete, and some owners, such as the New York/New Jersey Port Authority have adopted the AASHTO microwave test to determine the water content of the delivered concrete (as a partial check on w/cm (assuming that the cementitious materials are typically batched accurately) related to unintentional or deliberately added water).
3) *Quality Assurance/Quality Control Tests:* To document that the concrete supplied meets strength and other specification limits (a) at the change of ownership (the point of discharge from the truck) or (b) at the point of placement, to demonstrate that pre-qualified placing practices are being followed.
4) *In-Place Tests:* Using non-destructive tests (NDT) and/or performance tests on cores extracted from the structure to ensure that the combination of the concrete supplied and the placement and curing methods used resulted in achieving the owner-defined performance levels. This is required in the End Result Specifications (ERS) used by several North American highway agencies such as the Ministry of Transportation Ontario (MTO). MTO has provisions for both penalties and bonuses to contractors based on consistently meeting limits for strength, hardened air void properties and ASTM C1202 coulomb values of the in-place concrete. Since results will depend on both the concrete supplier and the contractor, it helps ensure coordination between them.

While there are many types of aggressive exposures, potentially requiring a multitude of durability tests, the common property to be minimized in all aggressive exposures is the “permeability” or more correctly the fluid penetration resistance of concrete. Therefore, adoption at least one performance test for measuring fluid penetration resistance is fundamental for specifying durable concrete in severe exposures.

Most deterioration processes involve two stages. Initially, aggressive fluids (water, ionic solutions with dissolved salts, gases) need to penetrate or be transported through the capillary pore structure of theconcrete to reaction sites (e.g., chlorides penetrating to reinforcement, or sulfates penetrating to reactive aluminates) prior to the actual chemical or physical deterioration reactions.

Therefore, a standard acceptance test or tests to measure resistance to ingress of aggressive fluids, or a related rapid index test, is fundamental to performancebased durability specifications.

However, before such tests are adopted in project specifications, they must not only be shown to be useful and reliable, they need be adopted in a standard and should include precision data based on inter-laboratory evaluations (as is required for ASTM test methods), in order to set realistic specification limits that take account of test variability. Many new tests have been proposed by researchers, but only a few have been found to be sufficiently robust to be adopted in recognised standards. There is some interlaboratory data published on potential tests for concrete cover quality.

Table 1. Damage scale for In situ condition survey of water tank (Bhaduria and Gupta 2006)

Condition Rating	Failure Class	Crack width (mm) and steel cross section area reduction (% age)	Description
01	Imminent failure	8.0, 30	Structural elements heavily cracked, wide cracks, highly corroded reinforcement, seepage of water, likely to fall any time.
02	critical	5.0, 20	Structural elements cracked, wide cracks, reinforcement corroded, and seepage of water, not likely to repair.
03	Serious	2.0;10	Structural elements cracked, reinforcement corroded, water seepage, repairable with difficulty by special techniques, e.g., epoxy grouting, epoxy treatment etc., for partial capacity use.
04	Poor	0.50:0	Visible cracks, minor seepage of water, initiation of corrosion few structural components damaged, reinforcement exposed in gallery, stairs flight corroded, repairable.
05	Fair	Hair-line cracks	Surface crack patterns, visible spalling/chipping of plaster, reinforcement not exposed, initiation of minor seepage, repair required.
06	Satisfactory		Reinforcement not exposed, no seepage, no leaching salt deposits, not well maintained.
07	Good		Reinforcement not exposed, no seepage, leaching salt deposits, visibly fair construction quality, not well maintained.
08	Very good		Visible excellent construction quality control, reinforcement not exposed, no seepage, no leaching salt deposits, periodically well maintained.
09	Excellent		Newly constructed and in excellent condition with respect to codal provisions of design, serviceability, detailing and aesthetic of concrete, workmanship and maintenance

IV. CONDITION RATING

Condition rating is a numerical index of damage level of the element and the whole structure, on the basis of in-situ tests and visual observation of the intensity and extent of damage and judging the urgency of repair. There are various methods available for evaluating the condition ranking of RCC structure.

These methods are as follows,

1) DER rating method [(D) Degree, (E) Extent and (R) Relevancy]
2) Artificial neural network method
3) Artificial intelligence / expert system
4) Fuzzy logic method
5) Delphi method

The assessment is based on physical deterioration as determined by measurable distress. The Condition Ranking / Condition Index (CI) are represented by a quantitative ranking between 0 and 100. 0 being the worst condition and 100 being the best condition. The index serves as guidelines for structures that require immediate repairs and further evaluation.

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Table 2 Condition Index Scale (Greimann and Stecker, 1990)

Zone	Condition Index	Condition Description	Recommended Action
1	85-100	Excellent: No noticeable defects. Some aging or wear may be visible.	Immediate action is not required
	70-84	Very Good: Only minor deterioration or defects are evident	
2	55-69	Good: Some deterioration or defects are evident, but function is not significantly affected.	Economic analysis of repair alternatives is recommended to determine appropriate action
	40-54	Fair: Moderate deterioration. Function is still adequate.	
3	25-39	Poor: Serious deterioration in at least some portions of the structure. Function is inadequate.	Detailed evaluation is required to determine the need for repair, Rehabilitation or reconstruction. Safety evaluation is recommended.
	10-24	Very Poor: Extensive deterioration. Barely Functional.	
	0-9	Failed: No longer functions, General failure or complete failure of major structural component.	

V. CORROSION

Reinforced concrete is the most widely used construction material in the world. Concrete provides protection of the encased steel, notably from alkaline, and is capable of withstanding the effects of time and stress under adverse environments. It, however, becomes vulnerable when exposed to marine environments, with chloride ion attack and carbonation being the most prominent factors inducing degradation. It should be noted that the plain concrete, without steel reinforcement, is generally stable and durable in the marine environment, but when steel reinforcement is added, durability becomes a major consideration because of the vulnerability of the steel to corrosion. The reason for exacerbated corrosion in the coastal environment is attributed to seawater's high chloride content.

This together with the presence of oxygen in marine, especially in zones subject to sea spray and splash, increases the risk of corrosion at marine environments. There are also other reasons for the exacerbated corrosion near the coast mentioned by like the animal and vegetable life in seawater, bacteriological activity and also sulphate-reducing bacteria can cause steel to corrode under anaerobic conditions.

The Euro-norm classification of environments is given in BSI, which defines a series of exposure classes for the typical environments to which concrete structures are subjected. These include no corrosion risk (X0), carbonation-induced corrosion (XC), chloride-induced corrosion (XD, XS), freeze/thaw attack (XF) and chemical attack (XA). Marine structures are subject to chlorideinduced corrosion from seawater, and therefore only exposure class XS is applicable unless the possibility of freeze-thaw is also present in cold climates, in which case XF may also be a consideration.

The main reasons inducing corrosion in coastal environments are summarized below:

1) Ingression of chloride and sulphateions by diffusion or other penetration mechanisms. Although it has been observed that the combined effect of chloride and sulphate ion attack causes corrosion, no experimentation yet has revealed the mechanism of both ions acting together.
2) Inadequate depth of cover over the steel reinforcement, or excessively porous, poorly compacted concrete, will increase the risk of ingression. Moreover, in the presence of oxygen and moisture, steel reinforcement will being corroding immediately.
3) Mineral contamination of aggregate, cement or water during construction, degrades concrete. In particular, severe levels of damage have been reported where seawater was used in construction.
4) Carbonation – the chemical reaction between carbon dioxide and cement hydration products such as Calcium Hydroxide and Calcium Silicate Hydrate (CSH) Gel phase – leads to the formation of Calcium Carbonate, which lowers the pH of concrete. This condition causes the despassivation of steel and lead to a situation to initiate corrosion within concrete elements.

A. *Steel Corrosion Resulting from Chloride Ingress*

There are some requirements in case of steel corrosion resulting from chloride ingress, Capillary absorption, hydrostatic pressure, and diffusion are the means by which chloride ions can penetrate the cover of concrete that protects the reinforcing steel. The most familiar mechanism is diffusion, the movement of chloride ions under a concentration gradient. For this to occur, the concrete is generally exposed to a continuous chloride bearing liquid phase resulting in a chloride ion concentration gradient.

A second mechanism for chloride ingress is permeation, driven by pressure gradients. If there is an applied hydraulic head on one face of the concrete and chlorides are present, they may permeate inward, as in submerged tunnels. A more common and rapid transport method is by capillary absorption into unsaturated surfaces. As a concrete surface is exposed to the environment, it will undergo wetting and drying cycles. When water containing chlorides encounters a dry surface, it will be drawn into the pore structure though capillary suction with the rate dependant on the moisture content of the concrete surface. Typically, the depth of drying is limited, however, and this transport mechanism on its own will not allow chlorides to penetrate to the depth of the reinforcing steel unless the concrete is of extremely poor quality and the depth of the reinforcing steel is too shallow.

B. *Deicing Salt Corrosion*

In the areas of North America exposed to freezing, the most widely used deicing salt spread on highways and bridges is NaCl, except in very cold climates where calcium or magnesium chlorides are used due to their effectiveness at lower temperatures. As well, in recent years antiicing has also been adopted where concentrated liquid brines (of up to 30% of various chlorides) are being sprayed on pavements prior to winter storms. With anti-icing, some of this concentrated brine will start to penetrate the concrete immediately, and this has led to increasedincidences of so-called “joint rot” where severe premature concrete damage occurs adjacent to pavement joints: this will be discussed more under freezing and thawing.

C. *Marine Salt Corrosion*

In several standards, marine exposure is treated as a separate exposure from other chloride exposures because it is really a more complex combined exposure. In marine exposures, while the main concern is reinforcement corrosion due to chloride penetration, there are also sulfates and magnesium in seawater, combined with freezing and thawing in some climates, and there is also abrasion/erosion due to wave action. The impact from the sulfates in seawater is relatively minor, so in ACI and CSA standards seawater is only considered as a moderate sulfate exposure, even though the sulfate concentration would normally be considered severe exposure. This is thought to at least in part be due to the competition between Cl^{-} and $SO4^{=}$ ions in the seawater for combining with the hydrated aluminate phases from cement and many supplementary cementitious materials. In seawater, some of the chlorides become bound in monochloroaluminate compounds Therefore, in seawater exposures, use of high C3A cement is beneficial because it increases the amount of chloride binding, and ACI and CSA standards allow portland cements with up to 10% C3A.

D. *Service Life*

There are limitations of diffusion-based test methods for service life prediction. The current test methods used for measurement of apparent diffusion coefficients, such as Nordtest NT443 or ASTM C1556, take time to complete, and are only suited for prequalification purposes where sufficient lead time is available. For acceptance and quality assurance, there are several rapid indextests that have been used including ASTM C1202, Nordtest NT492 and either surface or bulk resistivity. The index tests used for rapid assessment of chloride penetration resistance of concrete are not perfect and the precision of test results needs to be recognised in setting appropriate limits. Another limitation is that diffusion is not the only mechanism of chloride ingress, and given that diffusion is relatively slow relative to other mechanisms, predictions based on diffusion results alone are not conservative. The rate of chloride ingress from an external surface will also be depth-dependant as a result of variations due to imperfect curing.

In addition, chloride ingress will be slowed by adsorption or chemical binding of some of the penetrating chlorides into the solid phases. There is no standard test for determining the threshold chloride concentration that will depassivate embedded steel. Published values for this critical threshold concentration vary widely depending on the method used. There are several predictive models being used using different inputs and equations. While there is scatter in the predictions provided by each of them, they do provide reasonable ways of assessing the relative performance of alternative concrete mixtures in severe chloride exposures. Finally, given local variations in exposure conditions, concrete properties, as well as limitations of test method results, no predictive service life model can be expected to be perfect in its predictions. But even though imperfect, model predictions provide useful engineering guidance for evaluation and comparison of different durability approaches.

VI. CONCLUSION

Codes and standards need to adapt to the reality that only requiring design for the initial structural capacity and deflections of a structure without adequate attention to durability design is insufficient to provide structures with long service life in severe exposures. While some Codes have already adopted new approaches, most national standards simply set out basic exposure classes and deemed-to-satisfy requirements based on local experience and locally available materials. In addition, requirements in some standards for minimum cement contents and having to meet strength and performance limits at 28 days do not relate to durability performance and stifle the ability to develop more sustainable concretes. These traditional design approaches are often only indirectly related to durability performance for each exposure and, in severe and combined exposures, have sometimes been found to be insufficient for providing durable structures. They also do not allow for proper evaluation of the different performance of different cementitious materials and mix designs that all comply with deemed-to-satisfy Code limits on w/c and strength; such limits do not account for the large differences in resistance to fluid penetration of concretes made with blended cements or SCMs relative to those of portland cement alone; these differences can be demonstrated by adoption of a test method to measure such performance or setting limits for maximum rates of penetration.

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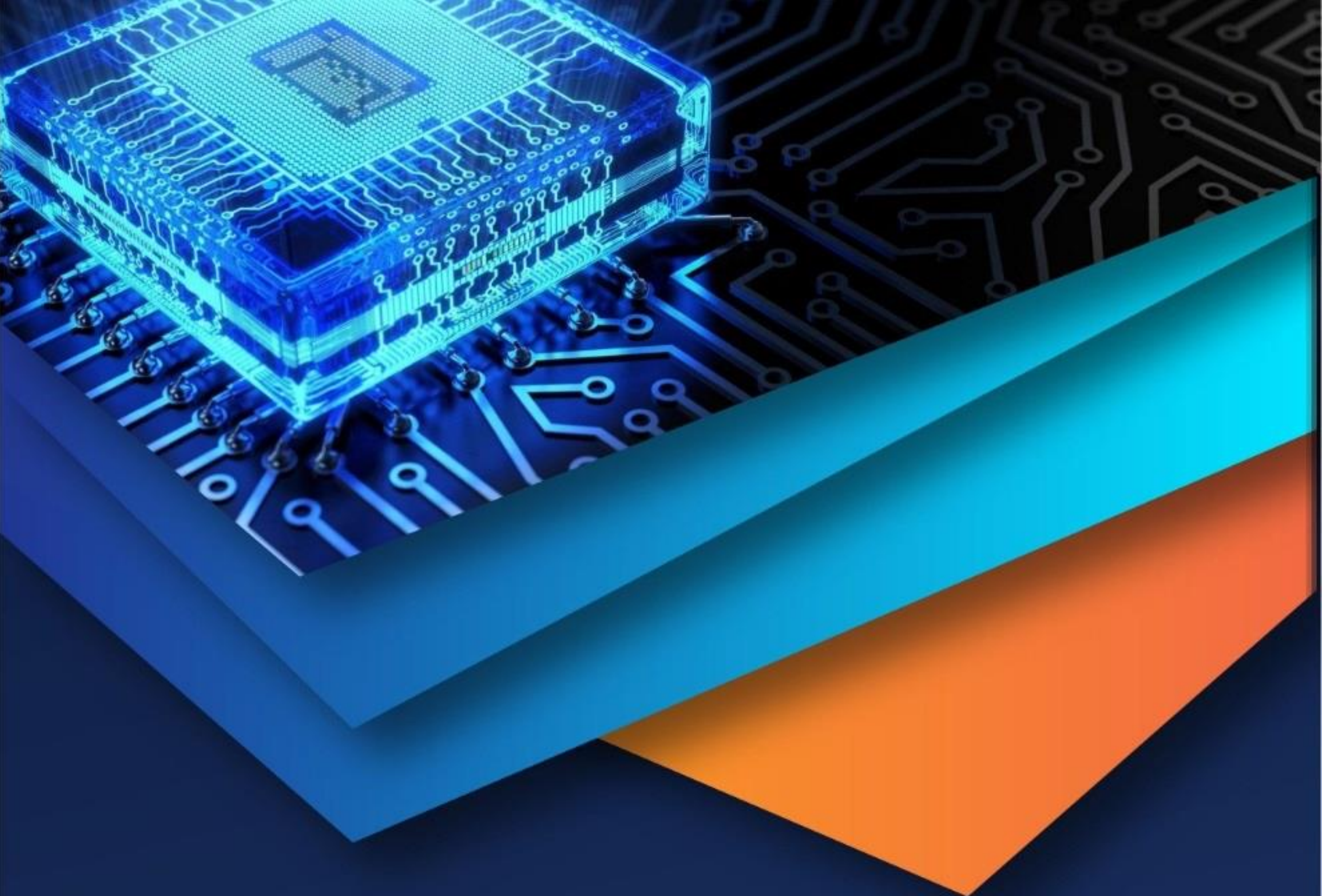

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