HARDENED CONCRETE PERFORMANCE GUIDELINES FOR CONSTRUCTION PROJECTS IN NEW ZEALAND

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Allied Concrete

Hardened concrete properties are fairly well defined in construction projects in New Zealand when compressive strength is the primary performance requirement. This paper considers other hardened properties of concrete such as tensile strength, drying shrinkage, thermal properties and durability, which are sometimes specified. The current approach appears to an example of the performance paradox where specifications attempt to maintain control without knowing what performance criteria are important.

This paper is a follow up to two previous papers and attempts to provide a comprehensive framework for ensuring hardened concrete properties are consistent with the designer's intentions. Specific guidelines will be given about the following issues:

- Predictions of compressive strength development
- In situ strength assessment using core strength testing
- Criticism of material properties derived from NZS3101 guidelines
- Tensile strength testing of concrete and applications
- Longer-term properties affecting durability of concrete

Quantifying performance in situ is greatly improved when designers understand that concrete microstructure may change significantly after 28 days, the role of control tests versus specialist tests, how to identify key performance factors and differentiating between science and marketing. Performance-based specifications are slowly been accepted in practice in New Zealand and its uptake will be improved when engineers have more successful examples to compare and gain a better understanding of performance issues. Examples of some of these projects that used performance specifications will be given in the paper.

INTRODUCTION

Hardened concrete properties are important for ensuring structural performance and durability of infrastructure and buildings. Designers require a range of hardened properties are achieved during construction, which require traditional techniques as well as newer methods. This paper considers the following issues related to the hardened properties of concrete:

- Understanding how compressive strength can be most accurately predicted during production of concrete
- Measuring the strength development of concrete in the structure at early ages
- Reliably estimating the in situ strength of concrete from core testing
- Controlling dimensional stability and thermal movement of concrete, how much can mix design changes influence these movements
- Can tensile strength be simply inferred from compressive strength and when should tensile testing be specified
- Understanding the difference between control and specialist testing for assessing the potential durability of concrete

Most of the above concern the strength of concrete while several are also focused on in situ performance rather than laboratory data. Achieving greater confidence with the above will improve the efficiency of concrete as a structural material.

![Schematic of hardened concrete properties](image)

**Figure 1: Schematic of hardened concrete properties of concrete**

While fresh properties of concrete are important for construction efficiency and affect quality, hardened properties control the structural, serviceability and durability performance. Achieving the design material properties therefore has a lasting effect on the performance of the structure.

**PREDICTING COMPRESSIVE STRENGTH**

Several countries already use water/cement ratio (w/c ratio) to predict the 28 day strength of concrete such that this information can be printed on the delivery docket. The relationship between w/c ratio and compressive strength was first established by Abram many years ago and requires the following measurements:

- Cement weigh scales must measure to an accuracy of 1%, which is already achieved as is required by NZS 3104 Concrete production standard
- Moisture contents of fine aggregate must be measured automatically using moisture probes as already happens in many modern RMCA plants
- Water used to slump the concrete must be electronically captured and added to the total batched water and this is standard at many RMCA plants
- Batching system must capture all material weigh ups and calculate the final water/cement ratio as the concrete load is dispatched
- Predicted strength of concrete can then be calculated based on historical records for the production facility and materials
Many RMCA plants already have the ability to accurately measure the final water/cement ratio of concrete leaving the plant and the next step would be easy to take. The biggest impediment to progress is confidentiality issues and the fact the older plants are able to capture this information but do not have the technology to display it in real time.

Cement hydration involves chemical reactions that generate heat and calorimetry is used to measure and interpret these processes. The total heat generated is measured using an isothermal calorimeter that operates at near constant temperature and measures heat flows induced by these reactions. The thermal power graph generated over the first 24 hours is able to quantify the degree of reaction and correlates well with compressive strength. Figure 2 shows the process of strength prediction process used in Europe.

Figure 2: Predicted strength of concrete using isothermal calorimetry

**COMPRESSIVE STRENGTH DEVELOPMENT**

Strength of concrete increases with curing time and this is quantified by the maturity index being the product of temperature and time. This maturity approach is used in ASTM C1074 to predict in situ strength of concrete and has several advantages over empirical estimates and non-destructive testing such as Schmidthammer. Figure 3 shows the typical relationship between maturity index and strength.
This approach has several advantages over traditional methods such as casting cylinders on site, which often are not able to replicate actual in situ temperatures. Maturity-based monitoring has the following advantages:

- Thermocouples can be cast into the concrete core that is less affected by external temperature fluctuations
- Sensors near the surface allow wireless extraction of information to be downloaded including temperature, maturity and predicted strength
- Correlations between maturity index and strength can be undertaken during the pour to allow for material and mix design variations

Post-tensioned industrial slabs still use traditional methods of monitoring in situ strength (field cylinders cured next to the slab in accordance with NZS 3109:1997). Internationally strength assessment in the field has moved to the maturity approach as per ASTM C1074. This allows more accurate assessment and is much more efficient and reliable. NZ stressing contractors need to consider moving to these systems given the positive experience in Australia and the United States.

**CORE STRENGTH MEASUREMENT**

Core strength testing of concrete is often fraught with problems and results in arguments over the following issues:

- Sampling done widely across the structure such that each core is a snatch sample
- Core diameters chosen of less than 100mm due to thin slabs or limited clearances
- Core testing done without hard plaster caps or grinding of the ends (rubber capping)
- Incorrect analysis of core strengths and acceptable limits given in the standard
The biggest issue is the way laboratory testing is being carried out around New Zealand. Rubber capping of the core ends is not in accordance with the standard and in some cases no capping of any type is used on sawn ends of cores. Cores diameters are almost invariably less than 100mm diameter and this means the restrained rubber capping rig does not work as intended. An example of this was core strength results from the CTV Building where local testing mostly used 70mm diameter extracted laterally from the columns was compared with retested cores done in the US with samples extracted longitudinally through the centre of columns (shown in Figure 4 with strengths of NZ results being lower than US results).

![Figure 4: Core strength comparisons for NZ and US laboratories](image)

Recommendations to be included in an updated version of IB74 include the following:

- Core ends must be either ground or hard plastered to NZS 3112 tolerances
- Restrained rubber capping system should not be used for core testing
- Cores should be tested in the as received moisture condition
- Mode of failure must be reported as either normal or shear
- Any obvious voidage or lack of homogeneity must be reported

Cores cannot be tested as if they are test cylinders since there are several key differences including diameter not been exactly 100mm, test samples are generally extracted from the structure at a moisture state well below saturated and compaction may be variable. Lower strength ranges are particularly vulnerable to poor end preparation and splitting induced by the neoprene capping dilating under load.

**TENSILE STRENGTH**

Tensile strength is sometimes specified when performance cannot be simply inferred from compressive strength due to the importance of this property in situations such as when designing unreinforced airport hard-standings. When specifying for tensile strength of concrete, the following should be considered:

- Whether tensile splitting or flexural tensile strength testing is appropriate (tests produce significantly different strengths – see Figure 5)
- What size test specimen should be used for testing (larger dimension generally give low strength and large beams are more vulnerable to handling damage)
- What level of tensile strength is required and at what age should this be achieved (tensile strength develops faster than compressive strength)
Structural specifications concerning tensile strength will often have supplementary requirements such as using crushed aggregates or limiting slump. These prescriptive requirements are generally unnecessary if the tensile strength has been explicitly specified and in some cases will adversely affect performance. An example of this was a specification concrete hard-standings at an airport where both tensile strength and crushed aggregate were required. This was due to poor joint performance of the older units where concrete had 40mm coarse aggregate supposedly for lower shrinkage. The use of such large aggregate meant that edges had poor particle packing and became vulnerable to failure when loaded. Intuitively the design engineer would blame the shape of the aggregate whereas aggregate size might have had a significant contribution.

**DRYING SHRINKAGE**

Drying shrinkage of concrete involves numerous material, environmental and structural factors, which results in widely variable in situ strains in concrete. Even laboratory testing of the free shrinkage of standard prisms is subject to several material factors. The main material factors affecting drying shrinkage are shown in Figure 6. Shrinkage reduces at higher water/cement ratios due to lower paste contents while very low w/c ratios appear to reduce drying shrinkage since a significant amount of autogenous shrinkage occurs before measurements start at 7 days.
The above shrinkage strains are based on an accelerated drying regime (AS 1012.13) and values need to be modified for restraint, size and environmental conditions. Shrinkage strains in concrete structures are therefore lower than laboratory shrinkage strains. Large raft slabs are typically 1-2m thick and only limited drying is possible from the top surface. As such typical drying shrinkage estimated for these structures may be as little as 30% of the laboratory shrinkage.

Guidance on drying shrinkage is now given in NZS 3101 bases on data from CCANZ TR11 and using AS3600/NZ bridge manual provisions. While this guidance is useful there are situations where this guidance may be misleading and further testing might be prudent. An example is when considering high strength precast concrete, especially when exposed to thermal curing. Recent testing has shown that such concrete typically has water/cement ratios of below 0.35 and rapid cement hydration will internally dry concrete. The highly impermeable nature of the concrete means curing is unable to restore saturated conditions. This might limit long-term strength development but does mean that drying shrinkage is significantly reduced, which is advantageous for large bridge beams.

**DURABILITY**

Durability of concrete is complicated by material, environmental and structural interactions, which makes predictions difficult. Deterioration of concrete can take many forms as shown in Figure 7. Research has however shown that applying simple prescriptive limits in some environments is able to significantly improve the potential durability of concrete. These form the basis of prescriptive recommendations in Chapter 6 of NZS 3101.
Durability of concrete has been shown to best controlled by limiting transport of harmful materials through the cover concrete. Several durability-based tests have been developed that are linked to transport processes such as diffusion, absorption and permeation. Performance-based specifications for durability have the advantage of targeting critical properties of concrete. The disadvantage of specifying durability testing is that these techniques are often complicated, tend to be expensive and the reliability is sometimes questionable. Very few durability tests are robust and quick enough to be used as control tests that can be undertaken by the contractor or concrete supplier.

Durability testing was required for a large wharf recently and this was extremely useful in confirming that the required chloride resistance was consistently being achieved. The Nordic chloride migration method was specified, which is expensive to undertake using commercial laboratories. During this project a limited amount of resistivity testing was also undertaken and this was found to have a good correlation with the more sophisticated chloride migration technique. Control tests such as resistivity are easy to undertake in a standard concrete laboratory and allow the chloride resistance to be quickly measured. This allows the supplier to optimise the concrete mix, batching and mixing for best performance.

**RECOMMENDATIONS FOR HARDENED PROPERTIES**

**Predicting strength**

Compressive strength of concrete can be accurately predicted from w/c ratio provided materials are consistent with historical data. Calorimetry can be used to predict strength more accurately being sensitive to material fluctuations affecting strength. At present most concrete is supplied in NZ without predictions of strength being considered before 7 days.

**Strength development**

Strength development of concrete in the field is currently measured using old technology that is not only inefficient but is also unreliable. Modern maturity systems have been shown to be
more reliable and are widely used overseas. These methods have been standardised and there is no reason why this approach could not be adopted in NZ.

**Core strength**

Measuring the in situ strength of concrete needs to be done reliably and current core testing practice in NZ is not always rigorous enough. Core strength testing procedure needs to be explicitly stated in standards and industry guidelines so there is no doubt about how strengths were derived. Guidelines are given in this paper about sample preparation, conditioning and testing to achieve more reliable results.

**Tensile strength**

Tensile strength needs to be clearly defined in terms of test type and size of sample to ensure the designer’s objectives are achieved. Specifying a performance requirement for tensile strength should mean that other prescriptive limits are not required. Tensile strengths tend to be more variable than compressive strength so it is important that acceptance and rejection limits are defined carefully.

**Drying shrinkage**

Laboratory testing of drying shrinkage provides only a comparative index of the potential strain of concrete in structures. The test was not designed to directly predict in situ shrinkage of concrete and measured values need to be corrected for size, restraint and environmental influences. Guidance is given in the latest version of NZS 3101 but caution is required since some interpretation is required and not all situations are adequately covered.

**Durability**

Predicting the durability performance of concrete requires specialist testing and is therefore not regularly done in practice. Simple control tests such as resistivity have been shown to be able to characterise microstructural properties that influence durability performance. Development of a suite of simple control tests could help improve durability of concrete since suppliers could optimise materials, mixes and processing.

**CONCLUSIONS**

The structural, serviceability and durability performance of concrete is dependent on design being converted into construction on site. Part of this is ensuring that material properties are satisfactorily achieved in the structure and this can only be done when structural specifications are relevant, practical and where possible are measureable.

Current specifications for hardened concrete properties could be enhanced by the following:

- Focusing on performance rather than prescriptive specifications
- Adopting new technologies that have been well researched and standardized
- Understanding that some test properties are extrinsic rather than intrinsic and may need some adjustment before application to the structure
- Ensuring that allowance is made for variability in results and non-compliance
Six questions may prompt engineers to develop better specifications:

**What** is the advantage of using performance-based specifications  
**Why** have the selected performance properties been selected for the project  
**When** should testing be done at ages greater than 28 days  
**How** can the correct mix of control and specialist tests be selected  
**Where** have tolerances and non-compliance protocol been outlined in the spec  
**Who** is responsible if specification was not effective to make improvements

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