Practical Assessment of Mass Concrete Construction for Wind Farm Projects in Remote Sites

Nick Canto
icubed consulting

Roderick Hetherington
icubed consulting

Abstract:

Wind Turbine Generator technology deployed in Australia has evolved to a point where each generating unit is producing power outputs exceeding 7.0MW. The generating unit consists of a steel tubular tower with a hub height in the region of 160m, and three blades with a rotor diameter of over 170m harnessing a sail area of approximately 2.2Ha. This equipment is supported on a reinforced concrete footing platform up to 4m thick, which, to sustain the imposed actions, can comprise upwards of 850 cu.m of concrete and 110 tonnes of reinforcing steel. Overall project size varies, depending on a wide range of factors, from 2 to 180 generating units with lifespans in the range of 30 to 40 years. Whilst today, the installed capacity of wind generation is comparatively modest in Queensland, there is a considerable pipeline of projects under development in the range of 50 to 150 turbines each, which will be completed as part of the state's increasing energy transition.

Meeting this future demand will conservatively require the construction of approximately 200 to 250 wind turbines per annum for the foreseeable future. This translates to between 4 and 5 turbine footings per week. Aggressive estimates for upstream infrastructure needed to sustain an emerging Hydrogen economy will increase this requirement threefold (Australia's Chief Scientist, 2019). Given these projects are largely situated in remote and regional communities, the logistical and technical challenges of delivering large volumes of high-quality concrete consistently, across an extended period and seasonal variations, are critical considerations during the planning, design and execution phases of these projects.

Wind turbine footings are highly loaded structures with a considerable fatigue spectrum that requires exacting standards in respect of strength, bleed, density, consistently, durability and thermal performance during the maturation process. An inappropriate concrete mix design and execution will result in unacceptable consequences to the durability and ultimate structural performance of the footing platforms.

Planning prior and during construction becomes vital, given the lack of local established infrastructure. The concrete mix designs must be simple, practical, and where possible make use of locally available resources while still meeting specified performance standards. Each wind farm typically requires minimum two mobile batching plants and the establishment of a reliable constituent supply chain. Concrete placement success is reliant on the timely replenishment of constituents without disruption. These batching plants must be capable of delivering concrete volumes at sufficient rates, and at the appropriate hour, to eliminate the failure of the typical monolithic footings.

This paper outlines the technical and constructability challenges faced by repetitive mass concrete pours in isolated regions of Queensland and, more broadly, Australasia. Drawing on the lessons learned from the author's personal experience in the sector, this paper presents the key issues for consideration to ensure that mass concrete works can be undertaken to a high standard without compromising on program or quality. It looks at key measures that can be deployed to manage potential durability concerns associated with Delayed Ettringite Formation, bleed settlement, thermal cracking and how to recover when planning fails.

Keywords: Wind Turbine, Renewables, Concrete, Construction, Project Planning

Introduction

This paper seeks to describe the challenges, risks and opportunities involved in planning and constructing the footing platforms for wind turbines, providing lessons learned based on the authors' personal experience in the sector as it has evolved from niche to mainstream. These experiences draw from an extended career over which wind turbine power generation outputs have increased more than tenfold.

Construction phase activities for a modern wind farm are generally intense, with staffing levels during construction on a single site upwards of 200-300 persons across a period of 2 to 3 years. They require the delivery of considerable volumes of materials to construct the significant works that supports the turbines, substations, maintenance facilities, power transmission lines, and associated infrastructure. The turbine footing construction in particular demands significant quantities of steel and concrete, and whilst there is a great deal of variability in turbine foundation construction across projects, in part due to their geographic location and site characteristics, several useful statistics have been derived from projects designed and documented recently to describe the scope of works required to support each turbine. Typically, a wind farm deploying 5 or 6 MW units will require an octagonal concrete mass gravity footing with face-to-face dimensions between 20 to 24 metres. The final geometry is governed by a combination of loading conditions and underlying geotechnical conditions. Footings of these sizes range between 550 to 850 cubic metres of homogenously placed concrete. Reinforcement rates for these footings would range from 60 tonne per footing for a smaller, lightly reinforced base, compared to 110 tonne per footing for a larger, more heavily reinforced base.

This paper outlines the technical and constructability challenges faced by repetitive mass concrete pours in isolated regions of Queensland and, more broadly, Australasia. Drawing on the lessons learned from the author's personal experience in the sector, this paper presents the key issues for consideration to ensure that mass concrete works can be undertaken to a high standard without compromising on program or quality. It looks at key measures that can be deployed to manage potential durability concerns associated with Delayed Ettringite Formation, bleed settlement, thermal cracking and how to recover when planning fails.

Catalyst for Building Wind Farms

Before describing the constructability impacts associated with wind farms, it is useful to understand the regulatory background, market dynamics and advancement of the broader energy sector at the time of this paper.

The Australian Wind Energy Market and Future Trends

The Australian wind energy sector has been growing steadily over the past decade. This was largely underpinned by the Renewable Energy Target, (RET), which was amended in 2015 to achieve 33TWhr of generation by 2020 (Renewable Energy (Electricity) Amendment Bill 2015, 2015). This target has been largely met and expanded upon by several projects underwritten by the ACT Government as part of their vision to source 100% Renewable Energy by 2020 (ACT Government, 2021).

The recent federal election has somewhat eased previous challenges faced by renewable developers as each of the states increase investment to meet Renewable Energy Targets. The Queensland Government recently released a new renewable energy plan increasing its commitment for 50% renewables by 2030 to 70% by 2032 and 80% by 2035. (Palaszcsuk, 2022)

The states and corporate Australia have committed to a transition to renewable energy to replace an aging fossil fuel fleet (Clean Energy Council, 2021). ACT, Tasmania and South Australia are today operating their power demands with near 100% renewable energy penetration.

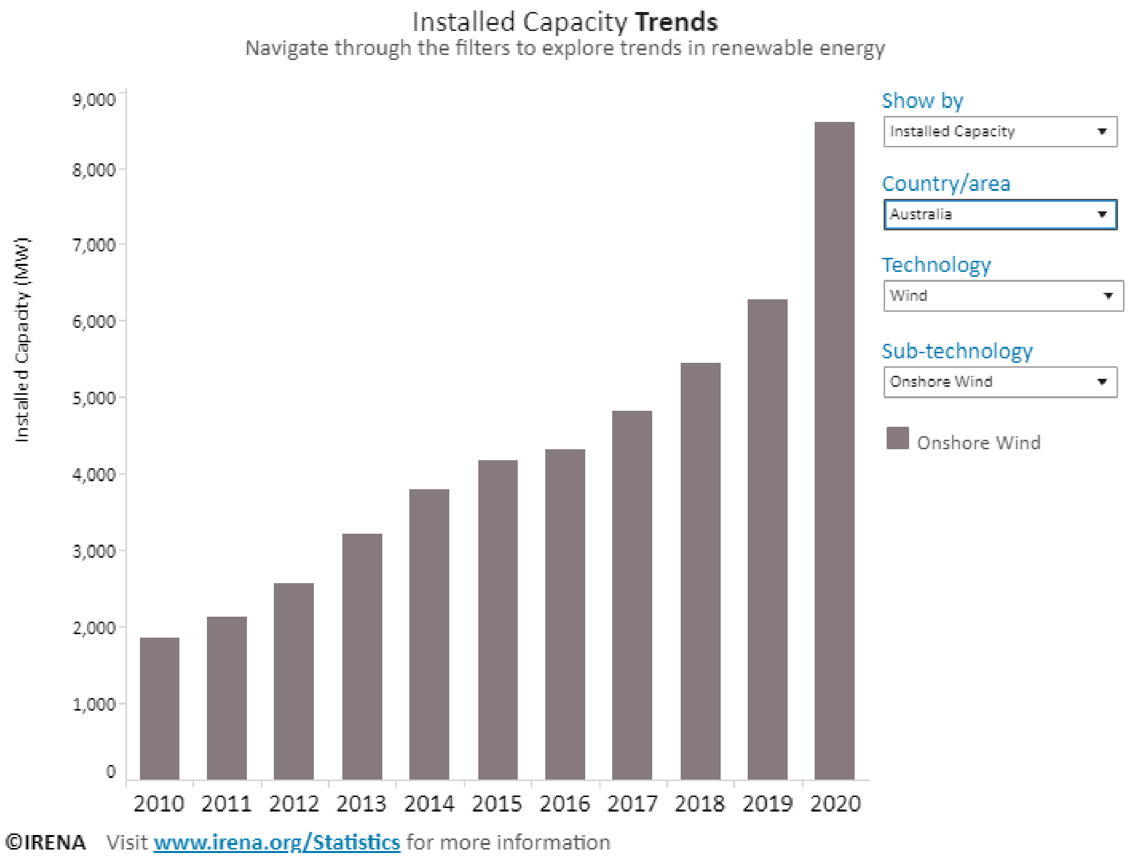
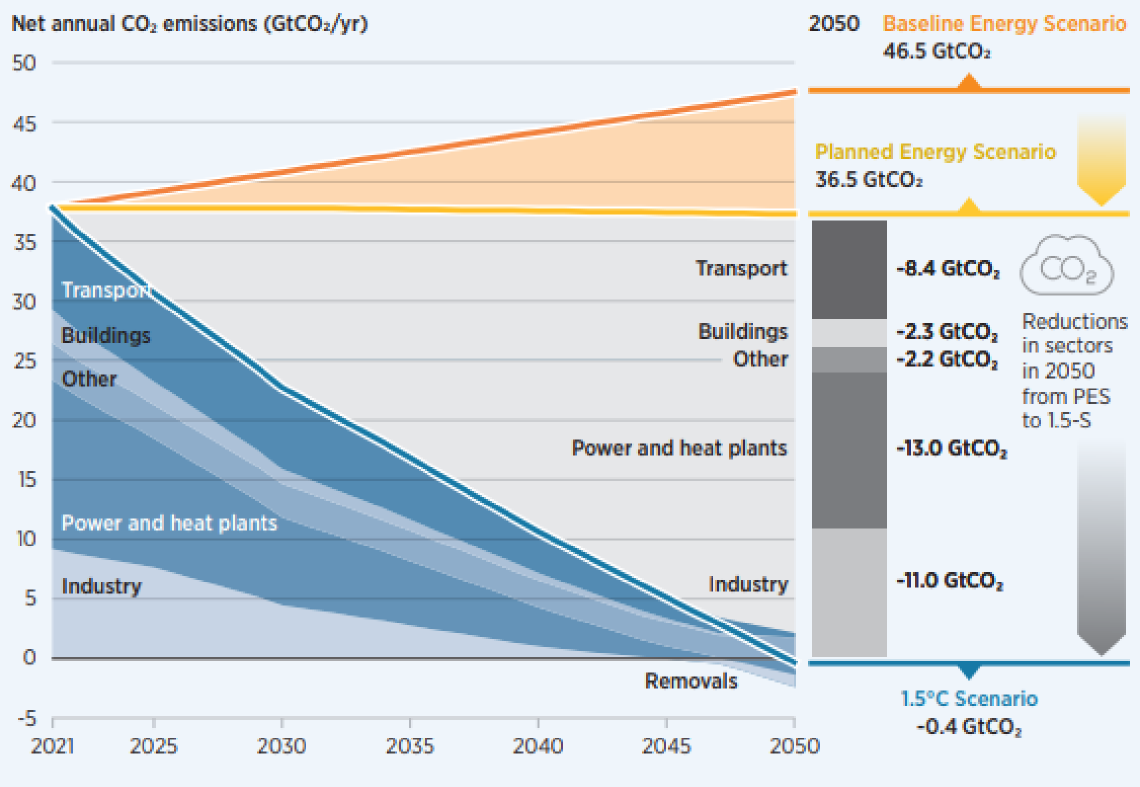


Figure 1: Australian Wind Generation, Installed Capacity Trends (International Renewable Energy Agency, 2020)

It can be seen from figure 1 that the rate of installation of wind generation is accelerating in Australia and this is set to increase in the future due to the cost advantage that this form of generation now holds over other forms of power production (Kompas, 2019).

Global Drivers for Change

The world is decarbonising (United Nations, 2021) and if Australia wishes to continue to be an active participant in global trade for goods and services, the nation is likely to be pressured into compliance with de-carbonisation trends. Australia is rich in renewable energy resources and has an opportunity to capitalise on this global trend. The International Renewable Energy Association (International Renewable Energy Agency, 2020) have published (refer figure 2) a planned energy scenario to decarbonise global energy consumption by 2050 and achieve a net-zero scenario.



Note: Gt = gigatonnes; PES = Planned Energy Scenario
Source: IRENA, 2021a

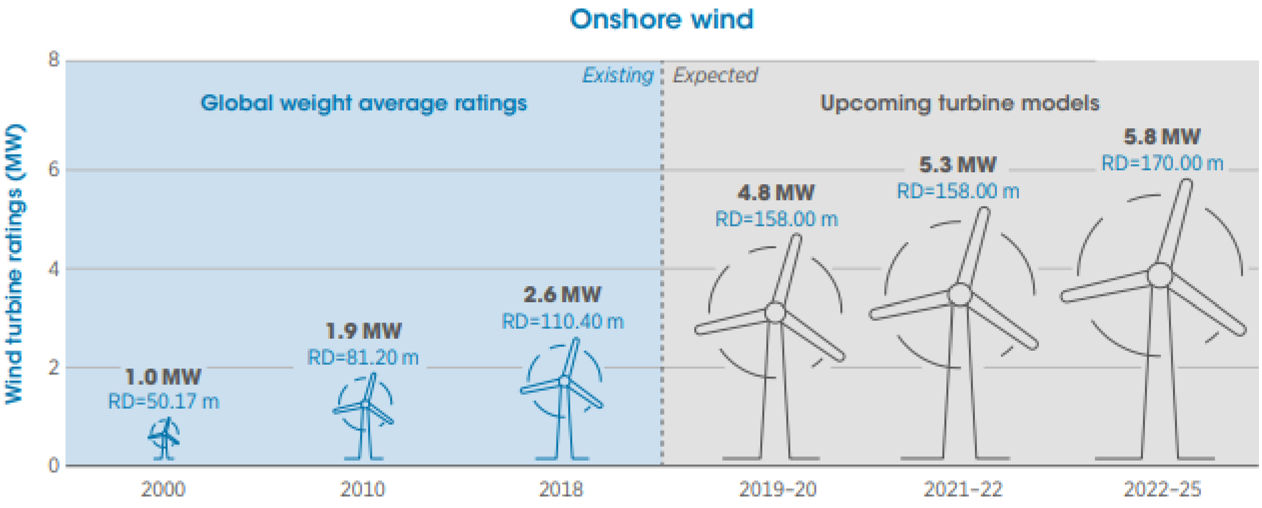
Figure 2: Planned Energy Scenario, 2050 (International Renewable Energy Agency, 2020)

Evolution of Wind Turbines

The first 22kW three bladed grid connected turbines were installed nearly 40 years ago in 1982. Today, onshore units are offered at more than 7MW and offshore units up to 15MW. Over the past 2-3 years the pace of development has been astonishing with Original Equipment Manufacturers (OEMs) developing more efficient machines capable of achieving high-capacity factors in low wind regions such as Queensland, on increasingly taller hub heights (refer figure 4).

Locally, the first mainland grid connected wind farm was commissioned in 2000 at Windy Hill, on the Atherton Tablelands. This project has an installed capacity of 12MW and consists of 20 x 600kW units, with a tip height of 68m and a rotor diameter of 44m (RATCH, 2021). The size and energy producing capacity of Windy Hill is dwarfed in comparison to the nearby Kaban wind farm, which reached financial close in September 2021. Presently under construction, it will have an installed capacity of 168MW and consists of 28 x 6MW units, with a tip height of 230m and a Rotor Diameter of 162m (NEOEN, 2021).

The MacIntyre Wind Farm Precinct, developed outside of Warwick, at 1,026MW generating capacity is one of the largest global single stage onshore wind farms (Acciona, 2022). Developed by Acciona, Ark Energy and the State Owned CleanCo, the project consists of 180, 5.7MW Nordex turbines with a rotor diameter of 163m on a hub height of 148m. Each of these turbines require foundations consisting of circa 650 cubic metres of concrete and 85 tonnes of reinforcement.



*denotes turbine developments happening from now and latest models available in that specific year.

Source: (IRENA, 2019c; Wind Power Monthly, 2019, 2018).

Figure 3: Onshore Wind Turbine Development (IRENA, 2019)

Modern wind turbines, on appropriately sited locations can produce energy at capacity factors of greater than 50% and are able to provide energy into the grid at rates less that the cost of fuel for both natural gas and high-quality thermal coal (Energy Matters, 2021). As storage technology and power to fuel technologies become more economically attractive, due to the weight of investment in these areas, renewable energy penetration is set to accelerate in the decades to come (IRENA, 2020).

Components of a Wind Farm

Grid connected wind farms comprise of three main elements: electrical balance of plant (EBoP), civil balance of plant (CBoP) and the wind turbine generators (WTG).

The electrical balance of plant comprises the part of the project required to collect energy from the turbines and transmit it via power quality and transformation equipment to the grid.
Key elements of the electrical system are:

- Main Power Transformer/s and connection substation including power quality equipment such as filter banks and reactive plant (refer Plate 1)
- Underground Electrical Cable, typically operating at 33kV (refer Plate 2)
- Overhead Power Transmission refer (refer Plate 3)

Plate 1: 220/33kV Substation – Dundonnell Windfarm, Victoria

Plate 2: 33kV MV Power Cable - Crudine Ridge Wind Farm, NSW

Plate 3: 275kV Overhead

The cBoP comprises the part of the project required to support the turbines and enable deliveries and erection of the turbine components.

Key elements of the civil infrastructure are:

- Access tracks between 5.5 – 6.0m wide rated to 250kPa for track mounted crawler cranes and axel load rated up to 36 tonnes per axle to facilitate the movement of mobile cranes (refer Plate 4)
- Hardstands for the main crane and storage of all components are in the order of 4,000 to 5,000 sq.m (refer Plate 5)
- Mass gravity concrete footings (refer Plate 6)

Plate 4: Typical Track – Ararat Windfarm, Victoria

Plate 5: Component and Erection Hardstand – Mt Mercer Windfarm, Victoria

Plate 6: Gravity Footing – Rye Park Windfarm, Victoria

The 'Wind Turbine Generators' encompasses the Transport, Supply and Install (TSI) arrangement for the project. This is the final stage of construction and includes all field testing and commissioning for the works. The typical erection process consists of:

- Delivery of componentry to site and laydown on the hardstand (Plate 7 and Plate 8)
- Pre-population of the tower with the initial tower segment(s) and grouting
- Erection of the remaining tower sections utilizing the 'Main Crane' (Plate 9 and Plate 10)
- Installation of all generating equipment and energisation

Plate 7: Tower Components – Bango Windfarm, NSW

Plate 8: Blade Components – Bango Windfarm, NSW

Plate 9: Main Crane Assembly – Sapphire Windfarm, NSW

Plate 10: Main Crane Operating – Dulacca Windfarm, Queensland

Wind farms comprise several major, interconnected elements which take many years of planning to deliver, and importantly, a major element that requires close planning is the wind turbine footings. The footings are essential in providing unwavering support for the towers with design lives of up to 40 years and are virtually impossible to repair or replace without considerable disruption and capital expenditure. Concrete, being the major constituent ingredient must therefore be produced and placed to exacting standards to avoid later disappointment.

Concrete Mix Design

The success of any construction project is based on the extent and relevance of the preparation. For the construction of WTG mass gravity footings, this starts with a well-considered, tried, and tested mix design using constituent ingredients readily available at the project location.

Materials

Typically, windfarm projects are situated in remote and regional locations, therefore locally available, high quality constituent ingredients are often limited. Cementitious products comprising, Ordinary Portland Cement, (OPC), Ground Granulated Blast Furnace Slag, (GGBS), Pulverised Fly Ash, (PFA) and Silica Fume, (SF) will comply with the relevant Australian Standards and will typically be derived from imported or limited Australian production centres. Projects can be at the mercy of the heavy aggregate and sand aggregate supply and quality which form the bulk of the concrete volume. Where the quality is lacking, concrete technology support from the concrete supplier and design engineer is essential to overcome potential deficiencies.

Often sought from local community potable water sources, water should be clean and free from materials deleterious to concrete in the plastic and hardened state and should comply with the requirements of the relevant Australian Standards.

Certain issues can only be addressed at the design stage, and so the project team must understand these issues prior to project design. Of note is the strain potential of the local rock. Certain isolated regions have rock that is only suitable for design strains greater than the recommendations of the Australian Standards. While design performance solutions exist to overcome such issues, for example increasing nominal crack reinforcement, it is critical to the project programme that such risks are understood and considered prior to the commencement of detailed design.

Summer and Winter Mixes

Typically, projects with more than 30 WTG's will have a construction program that persists across summer and winter, driving a need for at least two separate mixes and incremental adjustment. Generally, variable admixture combinations form the basis of the mix design changes for summer and winter, however heat management of the constituent ingredients is also essential in the production of concrete that is of acceptable quality.

Queensland's high ambient temperature conditions requires the inclusion of retarding agents to defer initial set of the concrete. Initial set increases the risk of a cold joint forming in the footing, intended to be monolithically cast, which can result in a failed pour. Managing initial set becomes increasingly important as the turbine sites are further away from the batching plant and may require over 90 minutes of transport from batch plant to the point of discharge. Conversely, winter mixes are typified by the addition of accelerants to enhance initial set times in single digit temperature environments. This is critical in regions with the potential to frost. Footings cast in these environments require protection from frost in the form of thermal blankets that must be installed the day of the pour (refer discussion in Thermal Modelling and Crack Prediction). For this to be possible, the mix design must be calibrated to stay 'workable' long enough to prevent the formation of cold joints, while setting fast enough to allow the concreting team to walk on the finished concrete surface the day of the pour.

Mix designs are typically calibrated to perform well in the peak of summer or the depths of winter. The construction teams should carefully consider the environmental conditions during spring and autumn, managing the mix design admixtures to prevent early set using a winter mix in warmer conditions or a lack of setting, using a summer mix in cooler conditions.

Admixtures are used to overcome any significant issues posed by aggregate or environmental shortfalls, however they are one a part of a range of levers that are used. Arguably more significant impacts can be achieved by managing the temperature of the constituent ingredients to ensure in winter, for example, the OPC will hydrate and initiate the important exothermic reaction required to achieve maturity. Conversely in summer, chilling of aggregates and the use of ice will ensure peak core temperatures do not exceed detrimental thresholds.

Mix Designs

Concrete mix design performance specifications should be set by the Design engineer, be fit for purpose and compliant with AS1379. Several mix designs are required for the construction of the footings. Primary purposes of each mix include:

- Flowable Fill
    - ‘Dental’ material to be placed between rocks where subgrade replacement with crushed rock cannot achieve mechanical compaction refer Plate 11.

Plate 11: Example footing requiring 'dental' flowable fill – Cattle Hill Wind Farm.

- N15 Blinding concrete
    - A simple pumpable low strength mix
- S32 Structural Concrete
    - Generally for the foundation Pad area
- S32 or S40, 10mm stone Structural Concrete
    - Smaller stone concrete to allow for introduction in areas of high congestion zone, often requiring higher strength in the high stress zone above the Anchor plate, refer Figure 4.
- S40 or S50 Structural Concrete
    - High strength concrete for placement in zones of high stress and fatigue stress zones. Typically in the plinth, immediately below the Tower Flange.

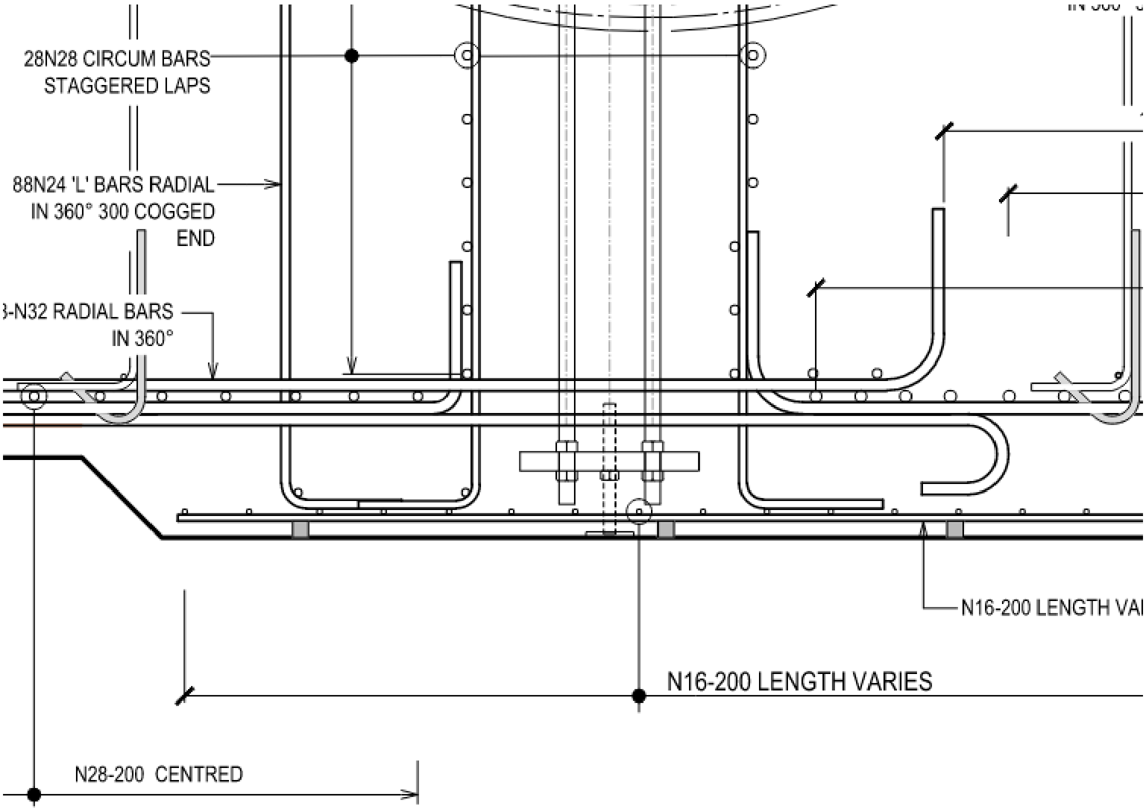


Figure 4: Detail of Congested zone, overlapping radial, circumferential and orthogonal bars - i3 consulting

Table 1 provides an example of a mix design performance specification table.

Table 1: Example table of Primary Performance Specification for Strength

Function	***Identification***	***Characteristic Strength at 28 days***	***Maximum Aggregate Size***	***Slump***	***Minimum Concrete Density***	***Min. Total Cementicious Content kg/cu.m***	***w/c Ratio min/max***
Flowable Fill	FF (Flowable Fill)	2MPa 1MPa @ 7 Days	Sand / Crusher Dust	200+	1850 kg/cu.m	5% TCC by mass	N/A
Blinding & Incidental Concrete	N15	15.0MPa	20mm	90mm	N/A	N/A	N/A
Structural Concrete	S32(LH)	32.0MPa	20mm	90mm	2340 kg/cu.m	280 [1]	0.45 / 0.55 [2]
Structural Concrete	S32(LH)10.120[3]	32.0MPa	10mm	120mm	2340 kg/cu.m	280 [1]	0.45 / 0.55 [2]
Structural Concrete	S40(LH)[4]	40.0MPa	20mm	90mm	2340 kg/cu.m	320 [1]	0.45 / 0.55 [2]

Note 1: Low Heat Mixes shall be either Triple Blend conforming with below or an alternative cementitious mix approved by the Design Engineer.

- The binder shall not comprise more than 50% OPC and 30% Fly Ash
- The binder shall comprise a minimum of 30% Blast Furnace Slag.
- 3.0-5.0% Silica Fume is strongly recommended in the structural mix designs to assist the control of settlement and bleed. Bleed shall not exceed 1% unless otherwise accepted by the Design Engineer

Note 2: W/C Ratio may deviate from specified following receipt of historical performance of the proposed mix.

Note 3: For first 50 cum of the pour or as required at the discretion of the pour supervisor for the concrete under and around the HD bolt cage bottom plate.

Note 4: The S40 concrete shall achieve a minimum characteristic strength of 50 MPa at 56 days.

Note 5: Structural Concrete shall have a target maximum drying shrinkage of 700µm with a maximum allowable drying shrinkage of 750 µm.

Suitability of Proposed Mix Proportions

During the project establishment phase, the Contractor should procure and review all relevant constituent quality information and prepare a mix design ready for trialling. The project team should have a clear understanding of:

- Proposed mix design targets including:
  - Strength, 28 & 56 Day

  - Bleed
  - Density
  - Drying Shrinkage
  - Workability, (Slump), including working time
  - Initial Set time
  - Material gradings
  - Pumpability
- Chemical composition of cementitious materials
- Proposed admixture products
- The nature and source of each material
  - Cumulative material grading
  - Petrographic assessment and AAR test results
  - Mechanical Properties
- The quantities of each material per cubic meter of fully compacted concrete, and;
- Full details of tests on trial mixes carried out in accordance with AS 1379.

Trialling the mixes is vital to ensure the strength and workability performance criteria are met and understood well in advance of a structural pour. Any change in the source of material or mix proportions trigger an updated review and trial process.

Concrete Trial Mix

Once the mixes have been designed and constituent materials are accepted for use, they must be trialled. Of particular importance is collecting data to verify the predicted adiabatic temperature rise. To collect this data, thermocouples are cast into a concrete hot box and temperatures logged for a continuous period of at least 7 days. Other performance requirements including placing temperature, workability, initial set time, density, bleed rate, strength, and shrinkage, should also be tested.

Trial Block – Hot Box

Trials are to be completed early to allow for design modification, if required, prior to structural placement. The trial block should be a cubic metre minimum with four (4) thermo-couples positioned as follows:

- Plan central – 100 mm above base
- Plan central – centre of concrete
- Plan central – 100 mm below top of concrete
- Within immediate area for block, shaded (ambient)

To ensure the true adiabatic rise is measured, the concrete block must be fully insulated with a minimum of 100mm thick polystyrene wrapped in insulation or thermal blankets for the period of monitoring.

Test Samples

From the trial block pour of the proposed structural concrete mix, fourteen (14) concrete cylinders should be taken. This allows for two (2) cylinders to be tested at 3, 5, 7, 14, 28, 56 and 90 days. This will allow for the preparation of a complete concrete maturation curve. Additionally, a shrinkage sample should be cast to validate the shrinkage performance assumptions.

Due to the depth of the footing, which may be 3 to 4 metres, and the potential for high amounts of cumulative bleed at the top surface, it is critical that a bleed test is completed during trials. This will give an early indication around the risks of concrete lensing below the top reinforcement. It will also provide the contractor with an understanding of the likely bleed risk at setting enabling the team to plan for finishing and thermal blanket placement.

Thermal Modelling and Crack Prediction

Background

This section provides discussion around the acceptance criteria for the concrete temperature limits (maximum and differential) adopted for the construction of mass gravity footings on a wind farm project.

Key to determining acceptance is via established assessment methods, such as those outlined in the Construction Industry Research and Information Association (CIRIA) C766 (Early-age thermal crack control in concrete) report Authored by P. Bamforth et.al. [CIRIA is a neutral, independent, not-for-profit organisation, who facilitate a range of collaborative activities that help improve the construction industry.] Whilst there are other options, the authors have extensive experience using CIRIA C766 and its predecessor including in field monitoring of, and correlation with, multiple mass concrete pours over more than a decade.

CIRIA report C766 (Early-age thermal crack control in concrete) was published in 2018, superseding previous versions. The methods developed by Bamforth et. al. are widely accepted globally as being the state-of-the-art practice in terms of assessment and management of risks associated with mass concrete construction.

ciria

Control of cracking caused by
restrained deformation in concrete

Figure 5: CIRIA C766

CIRIA C766 provides procedures to limit the extent of cracking to an acceptable level and, where appropriate, to avoid cracking altogether. These processes are aligned with the Eurocode requirements, however EN 1992 does not fully address design for early-age thermal cracking. CIRIA C766 has been developed to complement the EN 1992 design process and provide estimated crack widths that reflect more reliably than those observed in practice so that a robust and serviceable design may be achieved.

AS3600 – Concrete Structures (2018)

All mass gravity footings designed to facilitate the construction of wind farms in Australia must be prepared in accordance with AS3600, however there are deficiencies in this standard. To address these deficiencies EN1992 is used as an appropriate reference to establish design conformance requirements. Relative to early age thermal cracking, EN1992 has certain shortcomings also which are addressed robustly in CIRIA C766.

AS3600 provides little to no guidance on appropriate limits on maximum concrete temperature or thermal gradients. Typically, the minimum reinforcement provisions of AS3600 are greater than those required in the equivalent International Standards and are generally adequate to resist early age thermal cracking.

Measures to improve thermal performance of Mass Concrete Construction

There are several key factors that will improve the long-term performance of a mass concrete structure, and these are outlined in Table 3.4 of CIRIA C766. It is critically important that the best options available have been specified, these measures include:

- Angular aggregate shape
- Low aggregate co-efficient of thermal expansion
- Mid-range aggregate modulus
- High supplementary cementitious
- Water reducing agents to limit water cement ratio for required strength targets
- Placement temperatures – (AS1379 permits 35 degrees, which is generally far too high)
- Temperature differential – Limited to an absolute differential of 45 - 50 degrees, vertical, depending on the section thickness and resulting surface stains
- Ambient temperatures – Upper and lower limits specified
- Insulation – Specified during low ambient temperatures
- Reinforcement distribution – Not more than 200mm spacings

Acceptance Criteria

Thermal effects in mass concrete have the potential to impact the footing in two distinctively different ways, both having long term deleterious effects. These factors are the potential for:

- Delayed Ettringite Formation, (DEF)
- Thermal Shrinkage Cracking
- Restraint Shrinkage Cracking

Delayed Ettringite Formation

Delayed Ettringite Formation is a condition that can affect concrete that matures at elevated temperatures. Ultimately it will lead to a long-term reduction of strength and potentially internal cracking due to expansion.

DEF is a potential risk for Ordinary Portland Cement, where a curing temperature of 70 degrees Celsius or greater is realised. Where a minimum of 20% supplementary cementitious material is used, this thermal limit can be increased to 80 degrees Celsius (IFSTTAR, 2018), however often buffers are applied to these as a further precautionary measure.

Evaluating potential DEF risk in footings must be undertaken to understand the maximum allowable core temperatures on a project specific basis. They are heavily impacted by factors such as ambient conditions, element thickness, and concrete placement temperature. Upper limits are considered, and from this a theoretical core temperature value is obtained. To confirm the accuracy of the predicted outputs, an onsite trial hot box trial is specified to enable the data to be correlated to the theoretical model.

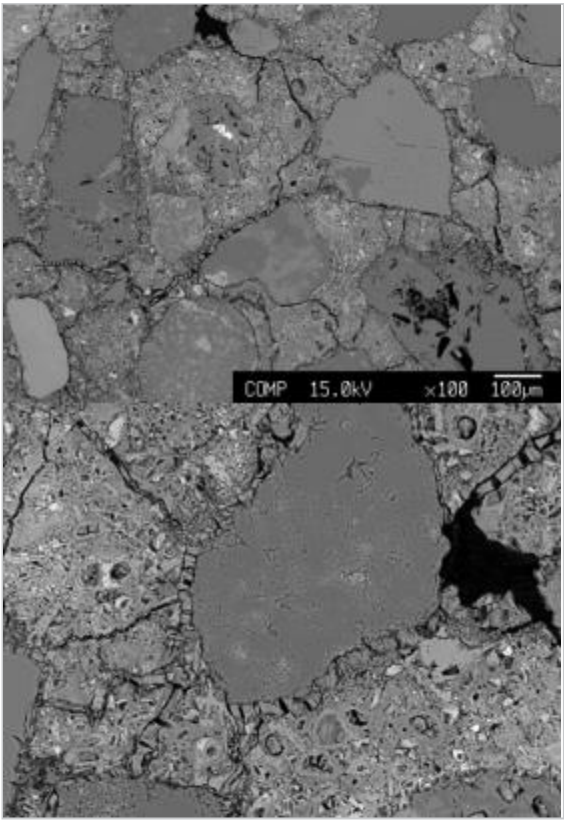


Figure 6: DEF fracturing of concrete matrix (Hanehara & Oyamada, 2010)

Thermal Shrinkage Cracking

Thermal shrinkage cracking may occur where differential temperatures through a cross section are large. For a mass concrete footing, it is important to note several facts:

1. The maximum core temperature will typically equate to the sum of the placement temperature and the Adiabatic Temperature Rise. This is because very little heat generated is lost to the environment, at least in the first 10-14 days from casting. That is unless internal cooling systems are provided, which are largely considered an action of last resort due to their cost and impracticality.

2. The surface temperature of the concrete will track that of the prevailing environmental conditions. It is therefore critical that exposed surfaces are insulated during cooler periods. It is impractical and entirely unnecessary to try to increase the concrete surface temperature to achieve an arbitrary absolute differential.

3. The susceptibility of concrete to cracking is influenced by materials selected and the concrete mix design. Careful consideration during this stage of the project can significantly reduce the potential for cracking.

As concrete cures expansion will occur due to the elevated temperatures produced within the element. This expansion and the resulting thermal strains may result in stresses from restraints that exceed the tensile capacity of the immature concrete. CIRIA C766 provides methods and guidance to assess this risk and, in cases where there is potential for cracking, a method for assessment of the likely width and spacing of these cracks. In severe cases the designer should provide for suitable reinforcement proportions to manage these cracks such that they do not compromise durability.

Some thermal cracking is reasonably expected to occur on mass footings and typically occur within the first 4 days after concrete casting. After this time, these cracks will either remain static or (most likely) reduce in width over time as the concrete reaches its in-ground equilibrium temperature. Thermal shrinkage cracking is, from a durability and structural perspective, no different to a drying shrinkage crack, however thermal cracking will reduce in width with depth from the concrete surface. The degree of cracking is a function of the reinforcement ratios. Lightly reinforced faces, such as the top, and specifically the side face, can be more prone to these influences.

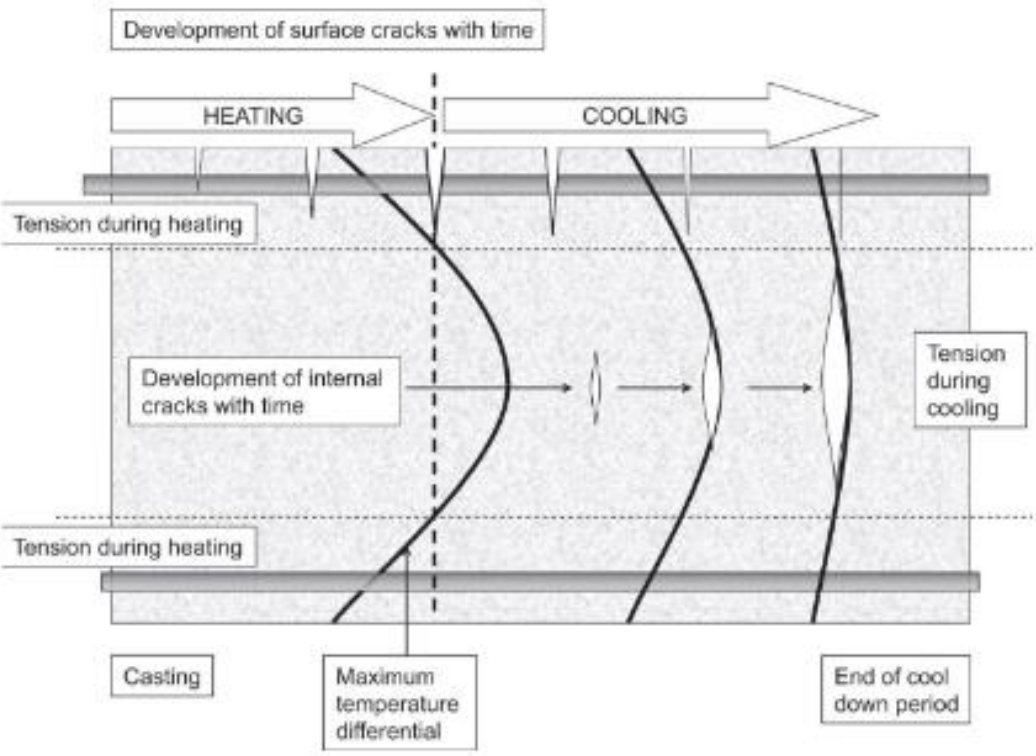
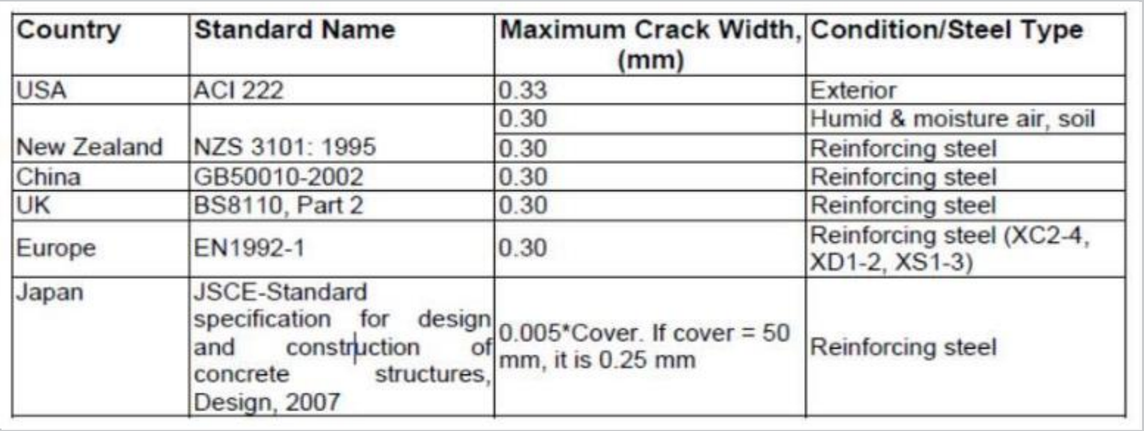


Figure 7: Schematic representation of the development of cracking in a massive element due to temperature differentials assuming no external restraint (Bamforth, 2018)

For controlling durability risks of concrete elements with early age thermal cracks, no specific crack width limits are nominated in the Australian Standard, AS3600 - Concrete Structures. Some guidance is however available from international standards and a summary is tabulated below.

Generally, significant crack widths for concrete durability in a non-aggressive environment are nominated in the order of 0.3mm. Table 2 provides a summary of some international codes, which are based on a design life of 50 years. We further note that the design life for the wind turbine footings vary between a nominal 30-to-40-year operational life. Based on a consensus of the international standards, a 0.30 mm crack width limit is considered appropriate for mass gravity pours.



Country	Standard Name	Maximum Crack Width, (mm)	Condition/Steel Type
USA	ACI 222	0.33	Exterior
New Zealand	NZS 3101: 1995	0.30	Humid & moisture air, soil
		0.30	Reinforcing steel
China	GB50010-2002	0.30	Reinforcing steel
UK	BS8110, Part 2	0.30	Reinforcing steel
Europe	EN1992-1	0.30	Reinforcing steel (XC2-4, XD1-2, XS1-3)
Japan	JSCE-Standard specification for design and construction of concrete structures, Design, 2007	0.005*Cover. If cover = 50 mm, it is 0.25 mm	Reinforcing steel

Table 2: International Standards - Crack Width Limitations

Further to this, prediction of crack widths due to thermal effects is undertaken prior to acceptance of the project concrete mix design and pavement methods for a given set of ambient conditions.

Plate 12: Thermal differential cracks repaired - Berrybank Windfarm Stage 2 - icubed consulting

Several international standards, including the American Concrete Institute (ACI 301-16: Specifications for Structural Concrete) stipulate that the maximum thermal differential within a mass pour should be limited to 20 degrees Celsius. This limit is an arbitrary limit derived from a combination of a simplified thermal expansion and strain calculation presented below.

$$\delta = L\alpha \, \Delta \, T$$

$$\varepsilon = \frac{\delta}{L}$$

$$\therefore \varepsilon = \alpha \, \Delta \, T$$

The 20-degree Celsius maximum differential is derived assuming a cracking strain ε_{cr} = $200x10^{-6}$ (microstrain) and the coefficient of thermal expansion $\alpha = 10 \times 10^{-6}$. A hard limit of 20 degrees Celsius (or occasionally 25 degrees Celsius, depending on the source) on the differential curing temperature is inappropriate as:

- Beyond this limit thermal cracking will occur, but is not necessarily greater than durability crack width limits
- It is an arbitrary limit that will change as the aggregate source rock changes and the coefficient of thermal expansion of the curing concrete changes
- Artificially keeping the surface temperature high enough to ensure a low thermal differential presents significant risk of introducing a “thermal shock” phenomenon when the concrete surface is finally exposed to the ambient conditions
    - Typically following seven (7) days of thermally protected curing
- The element thickness matters; hence the authors preference is to assess differential as a gradient over the element thickness

As such, engineers designing mass pours of concrete should be cognisant of the risks associated with thermal differential cracking and manage the site activities to keep the works within responsible durability limits without using blanket rules.

Project Predictions

Large wind farm projects are expected to require concrete casting operations across a period from parts of winter and summer. As such, there must be different control measures as the ambient conditions shift through the seasons, which should be foreseen and articulated in the project specification. It is appropriate to assess the potential thermal performance of the footing for this range of conditions and undertake both winter and summer placement simulations. These predictions and subsequent monitoring inform control measures such as:

- Heating of mixing water
- Chilling of mixing water and/or aggregates
- Thermal insulation placement and removal etc.

Site Considerations

Wind farm projects are serviced by onsite mobile batch plants. For projects with large volume pours, generally two plants are required to achieve the required placement rate, but more importantly offer protection against inevitable equipment failure. For expansive projects, multiple batching locations are required to limit the delivery times and required number of agitators. To facilitate a 700+ cubic metre pour in the Queensland summer, projects require batching capacity in excess of 120 cubic metres an hour. Ordinarily this is achieved through concrete produced from 2 batch plants with a combined capacity of 120 – 160 cubic metres per hour sized with the intent of pouring footings on consecutive days.

To facilitate these production rates, the placement operation requires two concrete pumps set up, pumping simultaneously, which also provides redundancy. Even at these rates, pours can take over 12 hours from commencement to finishing and placement of thermal blankets requiring multiple concrete crews per pour with staggered starting and break times. Extended pour times are exacerbated if there are breaks in service or dispatch of concrete outside of the workability limits, which are liable for rejection.

Batching, Mixing & Transporting of Concrete

Ready Mixed Concrete

Prior to any structural pours, the Contractor should have resolved all mix design studies. It is always recommended that each of the plants are calibrated and tested at full capacity prior to commencing the structural works for a project. This gives all confidence that the plant is operating as intended.

Transporting of Ready-Mix Concrete

Standard transportation requirements exist within the wind farm space. Concrete Agitator Trucks should be compliant with regulations and all concrete should be compacted and in its final place within 90 minutes of batching unless special considerations have been implemented in the mix design.

Risks with early initial set driven by high temperatures is to be managed through the mix design and trial process. Care must be taken that the concrete is batched within the limits of the approved mix design. The main risk here is the variable moisture content of aggregates stockpiles as the batching site is subjected to sporadic rainfall events. Any additional water that is required to manage workability at the pour must be completed by the supplier in line with the mix design provisions. For confidence it is recommended that any tempered mixes are sampled and tested.

Before discharging the concrete at the point of delivery the concrete supplier should provide the civil contractor with a delivery docket for each batch of concrete with standard records as per AS1379.

To allow for engineering forensics to take place should an issue occur, the following information should be added to the delivery docket at site:

1. The time of completion of discharge

2. Any water added signed by the pour supervisor

Compliance Testing

General

All sampling and testing of constituent materials must be carried out in accordance with the appropriate Australian Standard(s).

Strength

Compliance with the specified characteristic strength is required in accordance with the Australian Standard. Generally, the rate of sampling should be 1 test set for every 50 cubic metres of each mix design utilised on each day.

From each sample, it is recommended that 5, 100mm cylinders should be taken, one to be tested at 7 days and 2 to be tested at 28 days. Often the footings have later age strength requirements driven by fatigue damage during operation. As such, the additional cylinders are held to either:

- Confirm later age strength requirements, or
- For later age certification if a concrete load appears defective

Workability

Concrete workability can make or break a mass pour. Issues with workability have been known to double the placement time resulting in extreme quality and safety risks. Challenges with workability, an unfortunately common issue with low heat mixes, significantly increase the risk of cold joints forming in summertime and an inability for the concrete to set in sufficient time to safely install thermal blankets in the winter.

Concrete consistency is confirmed through slump tests and a constant feedback loop between the batch plant and pour supervisors. Slumps must be taken at every strength sample, but visual inspections should be completed on every truck before reversing to the pump hopper. The better the consistency of concrete and communication between the plant and the pour, the less likelihood there is of delays occurring. Whilst re-tempering of concrete should be permitted withing practical limits, this is a time-consuming process, breaks the rhythm of the pour and truck cycles. Getting it right at the slump stand is a key objective of any successful pour.

Handling and Placing of Concrete

General

Concrete must be transported, pumped, and placed in a manner that ensures contamination, segregation or loss of constituent materials does not occur.

Approval

All formwork and reinforcement in the pour must be clean and free from standing water, immediately before the placing of concrete. In circumstances where standing water will be difficult to pump out before the pour, the water may be pumped out during the placing of concrete or displaced by wet concrete under close supervision.

Placing of Concrete

In accordance with good practice, concrete should be deposited as nearly as practicable to its final position to avoid re-handling or flowing. Concrete should be deposited in horizontal layers to a compacted depth not exceeding 450mm to allow for appropriate vibration of layers with internal immersion vibrators.

Placing of concrete needs to be a continuous operation in which fresh concrete cannot be placed against in-situ concrete, once initial set has taken place. In WTG Footings of this size, this requirement means a minimum pouring rate of 80 to 100 cu.m/hr must be maintained to prevent the risk of pour failure. Generally, this placement rate is reduced during the start of the pour, when pouring the plinth and at the end of the pour when finishing and screeding operations have commenced.

If the pour has not finished and concrete has set, this would constitute a cold joint. Depending on the location of the jointing, it may be possible for the footing to be broken back and repaired. If the location of the joint is unfavourable, then a considerable risk exists that the footing must be demolished and re-constructed.

As per good practice guidelines, concrete should not be dropped into place from a height exceeding 2m. This will often mean that the contractor must construct pump hose ‘holes’ in the reinforcement to allow for the lowering of the pump hose to an acceptable drop height. In extreme cases, bars should be temporarily removed and re-fixed mid-pour when the plastic concrete is sitting high enough in the footing.

Sequence of the pour

The sequence of pours is to be arranged in a manner that minimises internal and external restraint and associated thermal and shrinkage cracking.

Detailed methods must be set out, workshopped and understood by all stakeholders before the pour can commence. These methods must include discussion of:

- Placement strategy
- Introduction of concrete to congested areas
- Protection of the hold-down bolts
- Finishing processes
- Number and positioning of vibrating needles
- Crew responsibilities and outlining of staggered rest times
- Who the pour supervisor is and what authorities they have
- Evaporative retardants
- Finishing and curing

Construction of the footing should generally proceed progressively from the centre region (inside the bolt ring) until such time as the concrete has ejected any air voids which may be trapped under the anchor base flange, for the entire circumference of the flange. At no time can concrete be introduced from both sides of the flange, until the concrete level at the perimeter of the anchor base flange is a minimum of 100mm above the base of the flange.

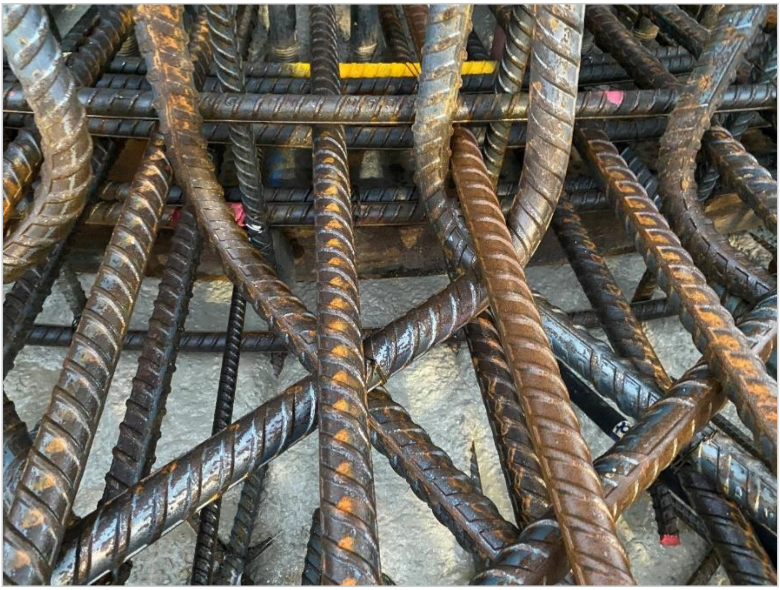


Plate 13: Concrete flowing under base plate to ensure no air voids remain - Rye Park Windfarm - icubed consulting

Construction should then proceed radially out from the centre region. Once the entire footing base has been poured to a level agreed by the project team, construction can continue from one side of the footing to the other, in layers not more than 300mm thick. The concrete is then poured continuously up the plinth, with considerations made for the construction of the grout trough immediately underneath the hold-down bolts template, or the preparation of green cutting of the top surface if the design stipulates a grout ridge.

Where different classes of concrete are specified, within the footing, special care must be taken to ensure that changeover processes are managed and clearly recorded in the concrete placement run sheet.

Compaction of Concrete

All concrete must be compacted to produce a dense homogeneous mass and be fully compacted with the assistance of vibrators. Sufficient vibrators in serviceable condition are required at the pour so that spare equipment is always available in the event of breakdowns.

All vibration of concrete should be carried out to ensure that no zones of under vibration exist in the footing. Care should be taken to avoid excessive vibration and consequent segregation of the concrete, however, due to the required placement rates, over-vibration is highly unlikely. Special attention must be paid to the formed edges of the structure that are known to exhibit zones of under-vibration, refer Plate 14.

A minimum of one serviceable internal vibrator should be provided for each 20cu.m. or part thereof, of concrete placed per hour. In addition to this, further serviceable vibrators will be required for practicality, fatigue management and to facilitate refuelling.

Plate 14: Example of cold jointing and under-vibration against the edge formwork - icubed consulting.

Concreting in Adverse Weather

Concreting activities must be planned so that they avoid storms, strong winds and heavy rains. However, in these remote environments, the ability to foresee inclement weather events is not always easy. As such, the project team should have prior arranged and agreed work methods to deal with such issues.

Wet Weather

No concreting can be carried out during periods of continuous heavy rain.

Hot Weather – Generally

Compliance with maximum temperature limits set within the good practice guidelines would mean that for extended periods over the summer months, concrete placement opportunities would not be possible. To deal with this, specific measures must be taken to allow for continuous concreting activities during prolonged periods of hot weather.

Management of Heat of Hydration

To manage thermal risks, concrete, when deposited must have a temperature in the range 5°C to 25°C, calibrated by a C766 model (where the upper limit is derived by way of engineering analysis of the concrete trials).

Maximum ambient temperature during concrete placement should not exceed 38°C unless special considerations have been made by the project team to ensure risks of cold jointing have been managed.

During warm conditions, precautions should be taken to manage the concrete placement temperature within the limits of the thermal modelling. Typical precautions include:

1. Generally:
   - Placing the concrete at a time of day when the ambient temperature is lower than the maximum

2. At the Batch Plant:
   - Shading aggregate stockpiles
   - Painting water tanks white
   - Insulating or burying delivery lines
   - Adding crushed ice to replace mixing water (in part) or chilling the water, and;
   - Injection of liquid nitrogen into the mixer (in extreme cases)

3. At the site:
   - Cooling the formwork by dampening with water sprays
   - Shading the work areas
   - Erecting wind breaks
   - Minimising the time for placing and finishing

Special attention should be paid to providing early curing for hot weather concreting operations. Management of surface evaporation rates at both the face of concrete during progressive placement and the unformed surfaces during finishing operations.

Management of Rate of Surface Evaporation

When the predicted evaporation rate during the intended casting period exceeds 0.75kg/m^2/hr, measures described above shall be taken to reduce the predicted evaporation rate (refer to Figure 8).

The forecast evaporation rate should be estimated using the latest available meteorological forecasts the day before the pour is set to commence. During placement, the evaporation rate should be monitored with measures taken to always prevent the evaporative rate exceeding 0.75kg/m^2/hr.

The use of registered evaporation retarding compounds is mandatory for all structural concrete placement for WTG Footings. To protect against jointing, an evaporation retarding compound shall be applied immediately after:

- Initial vibration of placed concrete, requiring further layering to achieve the total structural thickness, such that interface of layers is maintained in a fresh state prior to the placement of subsequent layers
- Initial screeding
- Initial bull floating and again after any finishing operations

To compute the evaporation rate of water from the exposed surface of the concrete, the following information is required:

- Air temperature
- Relative humidity
- Concrete temperature, and
- Wind velocity

Figure 8 should be used for estimating the loss of surface moisture from the concrete for various weather conditions. (Cement Concrete and Aggregates Australia, 2020)

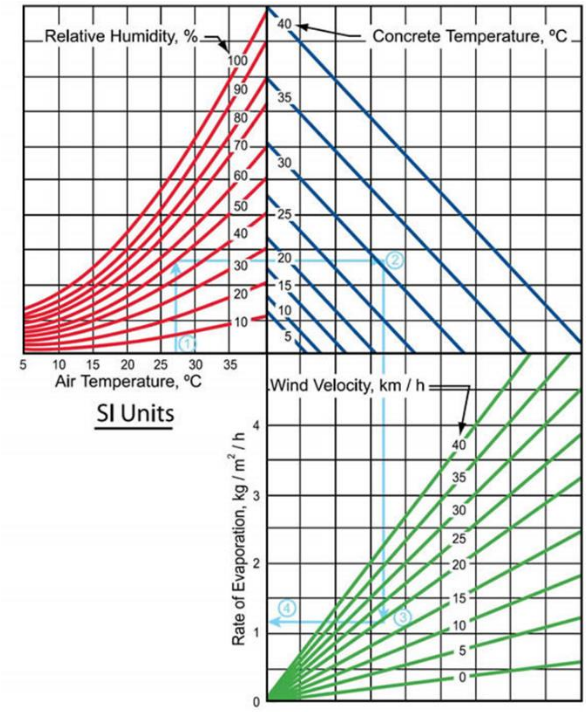


Figure 8: Calculation of concrete surface evaporation

Failure to manage the rate of evaporation will generally result in unsightly plastic shrinkage cracking of the concrete surface. Whilst the footing will ultimately be buried, repairs are time consuming, and the best strategy is avoidance by maintaining a damp surface applying Aliphatic Alcohol each time the surface is broken during the finishing process. Surface densification by power trowelling is also a very effective means of closing and densifying the surface of the footing. Typically, finish should be ‘power trowel – non-slip’ which can be achieved with two passes and will result in an acceptable and durable surface finish.

Plate 15: Typical Plastic Shrinkage Cracking - icubed consulting

Cold Weather

The methods used to protect concrete against rapid temperature changes and frost shall comprise defrosting of the aggregates and heating of the mixing water to bring the temperature of the concrete at the point of discharge to a minimum of 5 degrees Celsius. In no case shall concreting be carried out when the air temperature is below 0°C without freeze protection methods implemented at the site. No concrete can be placed against frozen ground or against hardened concrete or steel forms or reinforcement. In cases where freezing has occurred, water or other means can be used to de-frost the ground and reinforcement.

Fresh concrete requires adequate housing to keep the concrete at a temperature of not less than 7°C for 2 days. Typically, this is achieved through the placement of thermal blankets over concrete immediately following its initial set. Notwithstanding the 2-day housing requirement, newly placed concrete must always be adequately protected against night frosts. The cover should form a seal over all areas of exposed concrete and be maintained for at least 7 days. To prevent thermal shock when the blankets are removed, over the course of a few days, the blankets should be opened to remove the seal and allow some cool air into the protected zone to slowly drop the fresh concrete's surface temperature. Internal monitoring of concrete temperatures and differentials is helpful in guiding the timing and rate at which covers are removed.

Plate 16: Footing covered with thermal blankets - Berrybank Windfarm Stage 2 - icubed consulting

Considerable information can be obtained from production monitoring of mass concrete footings and whilst it is impractical and unnecessary to install instrumentation into every pour, a couple at varying seasonal conditions can be useful to demonstrate compliance and build trust in the analytical tools used during the design and trial phase. They can be used to inform early removal of covers for example when programs become stressed, or to enable assessment of the in-situ strength of the concrete due to the inherent accelerated curing conditions.

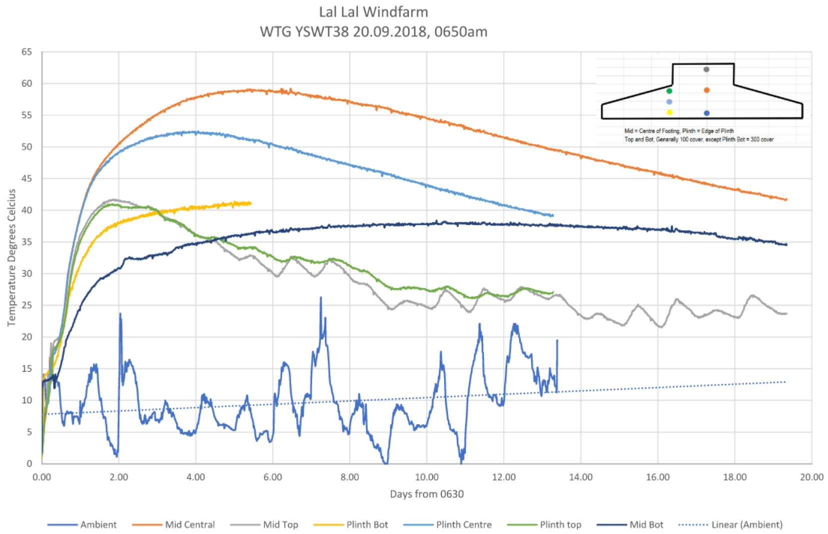
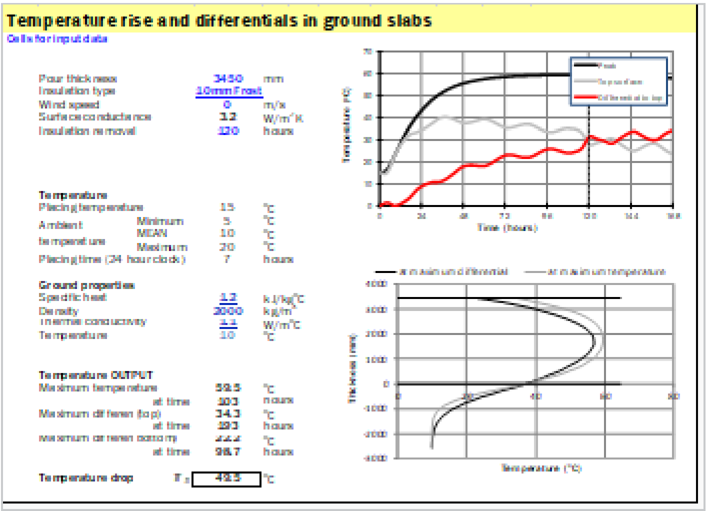


Figure 10: Monitoring records for 3.45m thick, 450 cu.m WTG Footing – icubed consulting


Temperature rise and differentials in ground slabs

Cells for input data

Pour thickness 3450 mm
Insulation type 10mm Frost
Wind speed 0 m/s
Surface conductance 3.2 W/m²K
Insulation removal 120 hours

Temperature
Placing temperature 15 °C
Ambient temperature Minimum 5 °C
MEAN 10 °C
Maximum 20 °C
Placing time (24 hour clock) 7 hours

Ground properties
Specific heat 1.2 kJ/kg°C
Density 2000 kg/m³
Thermal conductivity 1.1 W/m°C
Temperature 10 °C

Temperature OUTPUT
Maximum temperature 59.5 °C
at time 103 hours
Maximum differen (top) 34.3 °C
at time 193 hours
Maximum differen bottom 22.2 °C
at time 98.7 hours

Temperature drop T_1 49.5 °C

Figure 11: Prediction of Thermal Performance for 3.45m thick, 450 cu.m WTG Footing (Bamforth, 2018)

Figures 10 and 11 provide field records and the original predictions for a 3.45m thick WTG footing constructed in Victoria. The mix design for this project was a reasonably standard 70:30 Fly Ash Blend mix and the methods employed predicted a peak temperature of slightly less than 59.5 degrees and a differential of 34.3 degrees. Field monitoring shows actual results of 59.2 degrees and 31 degrees respectively, which is an adequate correlation to demonstrate the predictive methods are robust and can adequately inform the design and construction processes.

Curing and Protection

Once the pour has finished and screeding completed, an application of an approved curing compound must be applied. The chosen production should become stable and impervious to evaporation of water from the surface within 60 minutes after application to allow for the placement of thermal housing. Wax based products are generally prohibited due to the safety risk they pose walking on the sloping surface after the concrete has set and due to causing bond compatibility issues with subsequent sealing of the tower interface.

Construction Joints

No construction joints or cold joints are permitted within the WTG Footings. Reinforcement design is almost always proportioned and detailed for monolithic construction. The Contractor and project team must take all necessary precautions to ensure that monolithic construction is achieved. This may include measures such as:

- Maintaining a standby / back up concrete plant in the event of breakdown

- Altering set times of concrete by way of suitable admixtures
- Maintaining the surface of concrete in a fresh state by way of measures outlined in Management of Heat of Hydration

The plinth formwork should be designed to enable implementation of monolithic construction of the footing.

Conclusion

Wind farms will form a central part of Australia and Queensland's increased drive to transition to a decarbonised economy, requiring major construction activities, including the laying of substantial reinforced concrete footings, in succession, to support the wind turbines. Once the footing is laid there is very little opportunity for ongoing maintenance and consequences of failure in either the long- or short-term result in severe economic loss. It is important that the concrete production process is well integrated as part of the detailed design and that the consultant, contractor and concrete supplier collaborate to deliver optimal project outcomes in terms of time, cost and quality. Experience has shown that the number of methods available to assess the properties of concrete in its plastic and hardened states, across a wide range of maturation profiles are valid and corroborated within field testing. Early engagement, and effective collaboration, by all parties will result in successful outcomes for the completed footings.

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