ABSTRACT

Fresh concrete properties are poorly defined in most construction projects and this can be problematic when these specification requirements affect productivity and hardened properties of concrete. This paper discusses five main fresh concrete properties that have a strong influence on the workability and hardened concrete performance; slump, air content, segregation, bleeding and setting time. Each property is discussed in terms of its overall role in influencing fresh concrete properties and also how these affect hardened properties such as strength, dimensional stability and durability. Examples from case studies are also used to illustrate the role of these fresh properties have on concrete performance supplied to projects around New Zealand. Slump and air content are thought to be well understood but yet are sometimes specified in an impractical manner both in terms of limits and tolerances. Bleed rate, segregation and setting are generally assumed to be normal until there is an issue on site and then resolution becomes difficult without clear methods and benchmarks to assess these properties objectively. The issue is further complicated by adopting performance limits from other countries without any acknowledgement that local materials might differ significantly, which affects the perceived in situ performance. Outcomes from this paper are presented graphically to illustrate that these fresh properties are strongly linked and cannot be viewed or specified in isolation. Findings also include new research into fresh concrete properties including measurement of hydraulic bleeding in deep piles, setting time monitoring using calorimetry and rheological comparisons for special concrete mixes. Recommendations are made that will allow a better framework to be developed by concrete suppliers in order that fresh properties may be more accurately predicted and measured. This paper represents the first part of an overall specification guideline, the second part on hardened properties of concrete will be published in 2017.

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INTRODUCTION

Fresh properties of concrete are often not well defined in construction projects with these properties being either ignored or specified in an impractical manner that unnecessarily limits flexibility and/or productivity. Clearer guidance is required about these properties including slump air content, segregation, bleeding and setting time if this situation is to be improved. The most important fresh properties of concrete are illustrated in Figure 1 where these initial properties are related to practical outcomes such as workability, strength, dimensional stability and durability. This graphical representation shows how fresh and hardened properties are closely related and changes may be difficult to achieve.

Figure 1: Map showing the main fresh properties of concrete and influences

Fresh concrete specifications may include all sorts of additional requirements, which while having some relevance to concrete, generally do not need to be rigidly applied. This is particularly important when constituents and proportions such as water contents and mix design are prescriptively specified. Figure 2 shows some of the fresh properties that are sometimes specified and the main factors affecting each of these.

Figure 2: Diagram showing possible fresh properties of concrete that can be specified
SPECIFICATIONS

Specifications for the supply of concrete to construction projects tend to be a combination of prescriptive and performance-based criteria. Prescriptive elements in specifications are generally simple to achieve but sometimes these are in direct conflict with the stated performance required for the project [1]. Internationally there is a movement towards performance-based specifications whereas locally some structural designers appear to favour prescriptive-based approach where recipes need to be followed or specific materials included in concrete mixes such as chemical admixtures or additives [2]. This type of approach allows less flexibility and is often not effective in achieving the performance intended.

Figure 3 shows the difference between performance and prescriptive specifications used to control fresh properties. The prescriptive properties often have limited relationship with fresh properties and the rationale for their use is not clear. In reality, many construction specifications do not provide much guidance or limits on any fresh properties except for consistence level, which is usually measured with the slump test. Self-compacting concrete has the advantage that fresh property performance can be triangulated to some degree using spread testing, T500 time and visual stability index rating.

Prescriptive approaches are not without some scientific basis but generally the stated limits are not critical since high quality concrete can still be produced when outside these recommendations. For example, limiting the minimum temperature of concrete to 15 °C is impractical in New Zealand and setting is not an issue at lower temperatures of as low as 5 °C when using chemical admixtures that accelerate set times [3].

The fresh properties of concrete need to be clearly stated in construction projects in order that performance can be controlled and understood by all construction parties. This paper considers the following fresh properties in more detail; consistence as measured by slump, air content, bleed and settlement, segregation of high flow mixes and setting time.

Figure 3: Performance versus prescriptive specifications for fresh concrete
SLUMP TESTING

Slump testing measures the consistence of concrete from which the workability of a specific mix can be inferred but not accurately compared across a range of other concrete mixes. Slump targets have been increasing over the last few decades since water reducing admixtures have decoupled the relationship between slump and compressive strength. Unfortunately many specifications have ignored these developments while some have seen slump as the property that designers can use to compensate for a lack of site supervision or understanding existing standards [4]. This has led to several myths persisting in the structural engineering fraternity that are compared with generally accepted metrics shown in Figure 4 below.

<table>
<thead>
<tr>
<th>Myths</th>
<th>Metrics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Believed to be directly related to water content and therefore</td>
<td>Slump is a measure of consistence and an indirect measure of workability but does not predict hardened properties</td>
</tr>
<tr>
<td>strength, shrinkage and cracking</td>
<td></td>
</tr>
<tr>
<td>Water content of fresh concrete is the reason for slump variations</td>
<td>Material variations during batching</td>
</tr>
<tr>
<td></td>
<td>Chemical admixtures used in the mix</td>
</tr>
<tr>
<td></td>
<td>Traveltime and ambient conditions</td>
</tr>
<tr>
<td>Slump specified at less than 100mm</td>
<td>Slump nominated by contractor</td>
</tr>
<tr>
<td>Tolerances of ± 20mm specified</td>
<td>Tolerance for rep. sample ± 30mm</td>
</tr>
<tr>
<td></td>
<td>Tolerance for snatch sample ± 40mm</td>
</tr>
<tr>
<td>Sometimes believed that each truck is physically slump tested</td>
<td>Slump testing done every 75 m³</td>
</tr>
<tr>
<td>Testing frequencies &lt; 75 m³</td>
<td>More frequently when requested</td>
</tr>
<tr>
<td></td>
<td>Other loads are visually assessed</td>
</tr>
<tr>
<td>Some specifications will not allow retempering with water or</td>
<td>Special concrete cannot have water added on site (NZS3104)</td>
</tr>
<tr>
<td>super-plasticiser on site</td>
<td>Super-plasticiser can be used</td>
</tr>
</tbody>
</table>

Figure 4: Myths and metrics associated with slump testing of concrete

Performance
Specifications should avoid prescriptive slump limits and allow contractors to nominate an appropriate slump, which then becomes the performance target for that contract. Engineers who believe that no form of retempering is permissible on site should consider when last they have been held up in traffic on route to a meeting. The use of super-plasticisers to retemper special concretes has been done successfully for many years without affecting the hardened properties of concrete.

Innovation
Rheological testing of concrete is a powerful method to understand fresh concrete properties, especially when higher performance is required [5]. Rheology is the science of deformation and flow of material and may define the fresh properties in terms of yield shear stress (boundary between liquid and solid behaviour) and plastic viscosity (resistance to flow once liquid). These principles of rheology are used in modern concrete mixes in Europe that allow automation of the batching process and better control than visual assessment using dry batching plants. Slump meters installed on concrete trucks are a rough approximation since the meter is unable to differentiate between the differing rheology of concrete mixes, load size effects and are unable to be continuously calibrated using actual slump testing.
AIR CONTENT

The durability requirements for air entrainment of concrete in the New Zealand standards are poorly understood and needs to be clearly stated in order to avoid any confusion.

- Air entrainment does not provide any antifreeze benefit to fresh or setting concrete since all concretes are extremely vulnerable to frost damage during the first few nights after casting.
- Lower grades of concrete (typically 17.5-25 MPa and 17.5-30 MPa in the south of the South Island) require air entrainment since these concrete have relatively high water/cement ratios and are more vulnerable to freeze-thaw action.
- Lower strength concrete is generally air entrained regardless of exposure since there are other benefits to these mixes such as improved workability and material savings.
- Higher strength concrete may require air entrainment if the surface is exposed to multiple freezing cycles per annum (structures at higher altitudes or freezer rooms entrances).

The effect of external freezing is not immediately felt internally in concrete due to thermal mass effects and as water freezes below 0 °C when enclosed in capillaries and voids [6]. This process is illustrated in Figure 5, which shows how water initially freezes in more saturated capillaries and then flows towards partially saturated voids, allowing pressure relief caused by ice expanding by 9%.

![Figure 5: Concrete microstructure response to freezing internally](image)

Performance
Specifications for larger infrastructure projects sometimes require high levels of air entrainment of 5-6%. This air entrainment is specified by designers despite concrete strengths of 35 MPa and higher and mild environmental conditions with less than 50 frost cycles and minimum ground temperatures rarely falling below -6 °C. The cost of providing extra cement to meet this requirement is considerable and is totally disproportionate to the extra benefit if any at all. Coastal regions of New Zealand show little evidence of frost damaged concrete structures despite non-air entrained concrete being widely used in infrastructure projects for many years.

Innovation
The freeze-thaw resistance of concrete is determined as much by the volume of entrained air as by the distribution as measured by the spacing factor. Rapid spacing assessment techniques are now commonly used overseas to ensure a good distribution of micro-bubbles. Technology now also exists to be able to assess the air content of concrete in central mixers using acoustic sensors, which allows real-time measurement of a property that can be quite variable during production [7].
BLEEDING AND SETTLEMENT

Bleeding occurs in response to settlement of solid constituents and helps protect the surface from drying since excessive drying can cause plastic shrinkage cracking. The bleed rate of concrete reduces with increasing cement content and decreasing water content and porosity caused by improved particle packing (well graded, rounded particles have better particle packing). Evaporation of bleed water off the concrete surface is strongly influenced by wind speed and humidity as well as the air and concrete temperature. The potential for drying to exceed bleeding can therefore be estimated using the ternary diagrams shown in Figure 6 [8]. It should be noted that drying will quite often exceed the bleed rate when dealing with commercial or infrastructure concrete (e.g. graded 30 MPa and higher) and protection from anti-evaporative sprays or other measures are essential when concrete is cast outdoors.

![Bleed rate of concrete and Evaporation rate of bleed water](image)

Figure 6: Bleed and evaporation rate of fresh concrete

Performance
Bleed rates of structural concrete vary around New Zealand such that 40 MPa concrete with Auckland materials may bleed at above 0.6 L/m²/hr while concrete made with Christchurch material may bleed at less than 0.3L/m²/hr due to better particle packing and lower water demands. Some projects use Australian specifications that call for minimum bleed levels that are greater than normally achieved using rounded aggregates. Achieving these bleed rates can only be done by increasing water contents that in consequence will significantly increase shrinkage and creep characteristics of the hardened concrete.

Innovation
Deep foundations often require tremie concrete to have excellent water retention characteristics otherwise hydraulic bleeding will reduce the workability of concrete underground. Filtration tests such as the Bauer technique is able to assess the stability of concrete under realistic hydrostatic pressures (e.g. 5 bar pressure in the filtration test is equivalent to depths of 30m) [9]. Testing using this and other techniques has shown that prescriptive specifications that limit water contents to less than 170 L/m³ have no rational basis for tremmie concrete and will often prevent optimum performance in piling mixes.
SEGREATION

Segregation is the separation of constituents of a mixture leading to an uneven distribution of materials that can affect strength and durability of concrete. Structural concrete at normal slump levels of 100-150mm is sufficiently cohesive that segregation will only occur through poor placing practice or excessive vibration. Self-compacting concrete is more vulnerable to segregation due to the more fluid nature of the paste and testing is routinely undertaken to confirm the segregation resistance of SCC mixes (see Figure 7) [10].

**Performance**

Segregation testing shown above has varying levels of complexity with each intended for different phases of the production of SCC. The difference between site control, laboratory control and development trial testing is described below:

- Site control tests using visual stability index approach is simple to do on site and is done once the spread and T500 test is done on SCC
- Laboratory control tests are done periodically on SCC using the penetration or column segregation test and are more time-consuming and suitable for laboratory use only
- Development trials are only done initially when SCC is being developed and are intended to confirm the structural integrity of the material in situ

**Innovation**

Mineral and liquid stabilisers have become an essential component in SCC mixes since these materials can produce more cost effective concrete with lower cementitious contents [11]. Liquid stabilisers act on water molecules and effectively modify paste viscosity by long chain polymer interaction. Mineral stabilisers such as fine powders of aluminosilicates act as thixotropic and suspending agents and modify rheology of fresh concrete after shearing action has ceased. This thickens and stabilises the cement paste and reduces the potential settlement of aggregates.

![Figure 7: Segregation testing based on control or development requirements](image)
SETTING TIME

The definition of setting of concrete is the onset of rigidity such that final set is the start of strength development of the material. Setting reactions of cementitious materials are complex and involve a series of chemical reactions with calcium silicate and aluminate phases and also involve sulphate interactions from gypsum used for set control [12]. These chemical reactions are dependent on temperature with reaction rates doubling every 10–20 °C. Specifying limits on concrete temperature must be done with caution as lower limits of 15 °C and upper limits of 25 °C are unnecessarily restrictive and not consistent with the recommendations in NZS3109. Chemical admixtures allow a much wider range of concrete temperatures to be used in practice with controlled setting still possible between 5 and 30 °C. Figure 8 shows how retarders and accelerators are used to ensure setting of concrete remains within practical limits for efficient construction throughout the year. Setting times are influenced by concrete temperature, which may be quite different from air temperatures, especially early in the morning.

![Figure 8: Setting time versus temperature and accelerator dosage](image)

Performance
The New Zealand construction standard (NZS 3109) defines unfavourable conditions for casting concrete during cold weather and recommends that casting of concrete should only proceed when ambient temperatures are 2 °C and rising or 5 °C and falling [13]. The premise of these guidance limits for ambient temperature is to ensure that concrete temperatures do not fall below 5 °C as cement hydration will be severely curtailed even in the presence of set accelerating admixtures. The general guidance in NZS 3109 is not always reliable as casting into frozen ground on a sunny winters morning may severely retard setting and in contrast it may be possible to cast concrete in freezing weather if concrete is protected from the surroundings such that the concrete temperature remains above 5 °C

Innovation
Calorimetry is now widely used overseas to predict setting and strength development of concrete by measuring the heat generated from early hydration reactions of cementitious materials [14]. This measurement of heat outflow is able to track cement hydration reactions more accurately than simple setting time or compressive strength testing. Calorimetry using semi-adiabatic or isothermal techniques is rapidly becoming the preferred method of predicting setting times of concrete, assessing cement-admixture compatibility and is also starting to play a significant role in daily quality assurance of concrete production in Europe. In New Zealand calorimetry is sometimes used to assess finishing times on large industrial floors and to optimise accelerator admixtures used in cold weather.
Several fresh properties can be identified as being measurable unambiguously and may be relevant to specific projects. Table 1 gives more details about these fresh properties in terms of relevance, design limits, tolerances and standards. While specifications for consistence and air content have some justification for having limits that require relatively strict compliance, other fresh properties such as bleed, segregation and setting time are more rarely specified and limits are only generally applied in the event of lack of performance in that specific area. The relationship between fresh and hardened concrete performance is not that obvious and some limits specified for fresh properties have been shown to be detrimental to hardened properties of concrete [15]. For instance, specifications calling for slumps of 100mm for high strength concrete used in marine structures will not only limit productivity but will compromise durability since optimum compaction is much more difficult to achieve due to high levels of viscosity of these mixes.

Table 1: Fresh concrete guidelines, limits, tolerances and standards

<table>
<thead>
<tr>
<th>Fresh property</th>
<th>Relevance</th>
<th>Design limits</th>
<th>Tolerances</th>
<th>Relevant standards</th>
</tr>
</thead>
<tbody>
<tr>
<td>Consistence</td>
<td>Assesses workability of concrete and consistency of supply</td>
<td>Depends on the application - best nominated by the contractor</td>
<td>± 30mm for a representative ± 40mm for a snatch sample</td>
<td>NZS 3104 NZS 3109</td>
</tr>
<tr>
<td>Slump</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Air content</td>
<td>Freeze-thaw resistance and used for workability</td>
<td>&lt; 2.0 % mild 4-5 % mod. 6% extreme</td>
<td>± 1.5 % for all samples</td>
<td>NZS 3101 NZS 3104</td>
</tr>
<tr>
<td>Bleeding</td>
<td>Protects concrete surface from plastic shrinkage cracking</td>
<td>Bleed capacity is sometimes specified at 1-3%</td>
<td>None</td>
<td>ASTM C403 AS 1012.6</td>
</tr>
<tr>
<td>Segregation</td>
<td>Provides some robustness for handling of SCC</td>
<td>Column seg. &lt; 5% Penetration &lt;10mm</td>
<td>None</td>
<td>ASTM C1610 ASTM C 1712</td>
</tr>
<tr>
<td>Setting time</td>
<td>Predicts setting time of concrete provide conditions are controllable</td>
<td>Typically 6-12 hours depending on strength of concrete and environment</td>
<td>None</td>
<td>NZS 3112 Part 1:10 ASTM C232 IS 8142-1976</td>
</tr>
</tbody>
</table>

These fresh properties are transitory in nature with only air content being relatively consistent between the fresh and hardened state. The structural and durability performance is often not significantly influenced by these properties provided a practical value was achieved at the time of pouring and compaction of the concrete. This does not mean that these properties should not be considered in specifications but rather the relevance first needs to be understood by structural engineers before setting limits and tolerances, especially if these are at odds with general accepted values given in standards and guidelines.

Many of these fresh properties also have an influence on early age problems such as plastic shrinkage and settlement cracking, early thermal contraction and heat of hydration cracking. These early age issues are discussed in an earlier paper published in 2013 at the Concrete Industry Conference by NZCS [16]. Hardened concrete properties and performance will be discussed in the follow up paper to be published in 2017 at next year’s conference. A more detailed summary of all this information will be published by CCANZ in 2017 as a technical report to complement TR10 – Specifying concrete for performance.
CONCLUSIONS

Fresh properties of concrete affect both structural performance and construction productivity and these properties need to be carefully considered in specifications. Many construction projects in New Zealand have issues with structural specifications that either rigidly specify impractical limits for fresh properties, apply tolerance outside of the standard recommendations or completely ignore fresh properties until contractual disputes arise. Also of concern is that most structural engineering practices do not appear to have updated their concrete specifications for many years and most recent updates are largely wishful thinking clauses or statements that are at complete odds with modern concrete technology. This is not in their client’s interests and may be in breach of IPENZ ethics requirements.

Measuring the consistence of concrete using the slump test is a useful and simple method of ensuring concrete arriving on site is controlled and should therefore produce similar workability and setting characteristics. It is not however a direct measure of workability or strength and allowance needs to be for different applications and concrete mix designs. Air entrainment improves the freeze-thaw resistance of concrete when exposed to cycles of freezing but severity of exposure needs to be understood. Bleeding of concrete is important for slabs and panels exposed to drying that can cause plastic shrinkage cracking. It should be noted however that just as weather will influence evaporation rates, local materials and concrete mixes will have a significant effect of bleed rates and these need to be allowed for in design. Self-compacting concrete is vulnerable to segregation and a variety of tests have been developed to assess this property. It is important that the specified segregation test is relevant for that stage of the development or production process. Setting of concrete is affected by ambient conditions, particularly temperature, and chemical admixtures are used to ensure that control setting is achieved despite variable weather conditions.

REFERENCES