Early Age Tensile and Compressive Strength of Concrete – Impact on Predictions for Anchor Pull-out Capacity

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Abstract: The mechanical properties of concrete at early ages are of interest in particular to the precast industry. The safe lifting of precast at early age rely in-part on the concrete developing sufficient capacity to prevent premature pull-out of cast-in anchors. The design of these anchors partially relies on the efficacy of standard concrete compressive cylinder tests to reflect the in-place concrete strength and the tensile strength of the early age concrete. The capacity of anchors may be determined by the pull-out capacity design method (CCD) which is based on empirical research of anchors in concrete at 28 days or more.

The aim of this research was to examine the compressive and tensile strength development of concrete in early ages, compare this with data for mature ages (post 28 days) utilising both cylinder and core samples and correlate the data with pull-out anchor tests at various ages. In so doing, the research was to establish if the tensile and compressive strength development varied in early age concrete as the material matured and how this impacted on the anchor capacity predicted to test ratio. Research included testing of over 200 compressive and tensile cylinders, and companion tests of compressive cores and pull-out tests on cast-in anchors in slabs. Results show that the tensile strength development was different for early age concrete compared to mature aged concrete but the robustness of the CCD method was adequate for modelling.

Keywords: early-age, tensile strength, precast, anchors.

1. Introduction

Concrete passes through different states from the initial wet mixing to a stable state several months later. During the early stages of concrete strength development, inserts cast into precast panels depend on a predictable strength development, and therefore allowing the element to be lifted from the manufacturing facility to on-site placement. Fracture Energy and Modulus of Elasticity are the controlling material parameters that affect the tensile strength gain (Bazant 2002). Concrete upto 3 days old, and loaded near the concrete tensile capacity, will cause a fracture surface to propagate through the mortar mix. At early concrete age, and near the lifting inserts ultimate concrete capacity, the induced stresses transmitted through the lifting insert during the precast panel lifting process, are unlikely to have sufficient energy to shear the course aggregate.

Understanding the complete behaviour of concrete subjected to tensile loads is inevitable in precast lifting design, and especially during the lifting process of precast elements. The relationship between compressive and tensile concrete behaviour is specified in Australian Standard, AS3600-2009 Concrete Structures, and this standard defines the characteristic uniaxial tensile strength, as:

$$f'_{ct} = 0.36\sqrt{f'_c} \qquad \text{(EQ 1.1)}$$

Whereas the uniaxial tensile strength is also defined in AS3600:2009, and can be determined from the measured splitting tensile strength, if tested in accordance with AS1012.10 splitting test.:

$f_{ct} = 0.9\, f_{ct.sp}$ (EQ 1.2)

Where:

$f'_{ct} = Characteristic\ uniaxial\ tensile\ strength\ of\ concrete$
$f'_c = Characteristic\ compressive\ (cylinder) strength\ of\ concrete\ at\ 28\ days$
$f_{ct} = Uniaxial\ tensile\ strength\ of\ concrete$
$f_{ct.sp} = Measured\ splitting\ tensile\ strength\ of\ concrete, as\ per\ AS1012.10\ Splitting\ Test$

Darwin (1996) also presents a relationship of direct tensile concrete strength to characteristic compressive strength of mature concrete:

$\mathrm{f_{ct}} = \mathrm{g_t} \times \sqrt{\mathrm{w_c} \times f'_c)}$ (EQ 1.3)

Where:

f_{ct} = Direct Tensile Strength of concrete
g_t = 0.0069
w_c = Unit Weight of Concrete (kg/m^3)
f'_c= Characteristic Compressive Concrete Strength (MPa)

The tests covered by this paper include the comparison of various tensile strength tests, including: Cored cylinder compressive tests, in-direct splitting tensile test, uniaxial direct tensile tests, and cast-in lifting insert tensile tests. Various concrete mixes were tested and appropriate tests were compared against a moulded cylinder compression test.

The Curtin University undergraduate work of Wake (2010), Kocevski (2011) and Zielinski (2012) contributed to the tests included in this paper as part of their final year project.

2. Concrete tensile behaviour

The behaviour of concrete subjected to tensile loading has been represented by several researchers (Hughes 1966, and Evans 1968) where they obtained a stable and complete stress-strain diagram of concrete in direct tension. The tensile stress-displacement curve of concrete, figure 1, shows the curve, up to 75%, as almost linear, thereafter the pre-peak nonlinearity due to micro-cracking occurs. The softening response corresponds approximately in two parts, the first a descending one in which strain localization occurs and the second the later descending part with a long tail (Nomura 1991).

It has been confirmed that substantial non-linearity before peak load is attained (Shah 1994). Point A corresponds to about 30% of the peak load up to which propagation of microcracks of internal voids is negligible. Point B corresponds to about 75-80% of the peak load, where the cracks propagate between A and B and are isolates and randomly distributed over the specimen volume. According to Shah the tensile stress is uniformly distributed in the direction of loading over the specimen length. Between B and C the microcracks start to localize and the distribution of tensile strain in the loading direction is no longer uniform over the specimen. Beyond the peak load the tensile strain within the fracture zone continually increases, whereas the material outside the fracture zone starts unloading.

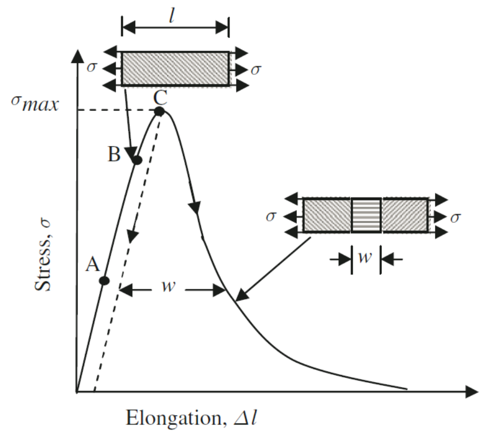

Figure 1 – A typical stress-displacement curve of concrete, *(w = Length of crack zone)*

The tests discussed in this paper recorded the maximum load post the elastic phase and in the plastic phase of a typical concrete stress-strain curve.

3. Tests

A typical concrete mix, used in the Australian precast industry, was used throughout all series of the tests; being a maximum of 20mm course aggregate, a typical 0.4 water/cement ratio. Nominal slump was 80mm +/-5mm.
Concrete compressive strength at time of test, f_c was recorded by means of cylinder compression tests, prepared in accordance with AS1012.2-2009 Determination of compressive strength. The mean of this cylinder compressive strengths were calculated, f_{cm}, for each panel test

3.1. Cored cylinder compressive tests,

Wake (2101) and Kocevski (2011) assessed the compressive strength development by coring two identical precast concrete panels. The precast concrete panels measuring 2600mm x 1100mm x 150mm deep, were cored in predetermined locations shown in figure 1. Coring was undertaken after 24hours, 72hours, and 28days. The cores were drilled, prepared and compressive tested as per the standards (AS 1012.9 – 1999 and AS 1012.14 – 1991). 69mm diameter and 110mm diameter cores were taken for compression testing.

Figure 2: Panel 1 coring locations, showing the 69mm and 100mm cores

3.2. In-direct splitting tensile test,

The splitting tensile strength test was conducted on concrete specimens of 150mm diameter and 300mm in length. The testing has be in accordance to AS1012.10-2000 Determination of indirect tensile strength of concrete.

Kocevski (2011) & Barraclough (2011 & 2012) tested the tensile cylinders after ambient curing at, 24 hours, 72 hours, 7 days and 28 days. The cylinders were prepared and tested according to the Australian standards (AS 1012.9 – 1999 and 1012.10 – 2000). Zielinski (2012) tested the Indirect splitting tensile strength testing, after ambient curing, at 1 day, 2 days, 3 days, 7 days, 21 days and 28 days.

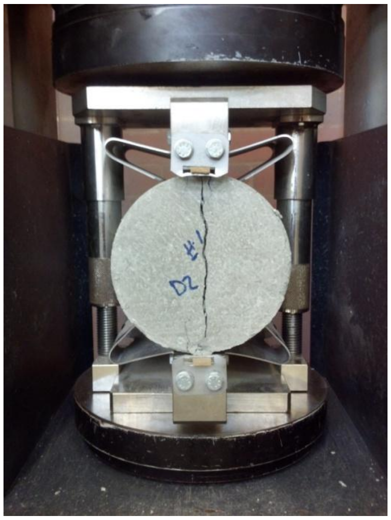

Figure 3: Splitting tensile cylinder test setup

3.3. Uniaxial direct tensile tests

The direct tensile cylinders where made up of 100mm diameter x 200mm length cylinders with a reduced centre at 30mm as illustrated in Figure 4. This is to precipitate a fracture surface across the reduced section. Direct tensile tests were carried out at 1 day, 2 days, 3 days and 7 days. Zielinski (2012) & Barraclough (2012) assessed the direct tensile cylinders which were also tested at early concrete curing ages to further test the relationship between tensile and compressive strength and the compare these results against the Brazil tensile results.

Figure 4: Direct tension test specimen

The cylinder throats reduced the cylinder diameter by 40mm, with a 30mm long reduced section, where the plastic throat was stripped after demoulding. After de-moulding, the ends of the cylinder were prepared in accordance with AS1012.8.1

3.4. Cast-in insert tensile tests

The headed anchors were installed using the puddle-in method to an embedment depth of 50mm. Zielinski (2012) placed the anchor so that the embedment depth, h_{ef}, allowed sufficient breakout area and reduced any possible impact on the edge of the panel or remaining foot anchors. A total of 5 foot anchors, per panel, were installed in locations as per Figure 5, and a total of 6 panels were cast.

Figure 5: Test panels with cast-in insert headed anchors

4. Results

4.1. Cored cylinder compressive tests,

The results of the cored cylinder tests for less than 3 days are depicted below, noting the moulded cylinder test cylinders (labelled as 'Cylinders') is following a strength gain gradient different to the cored test results (labelled as 'Series 1/2/3 Panel 1/2').

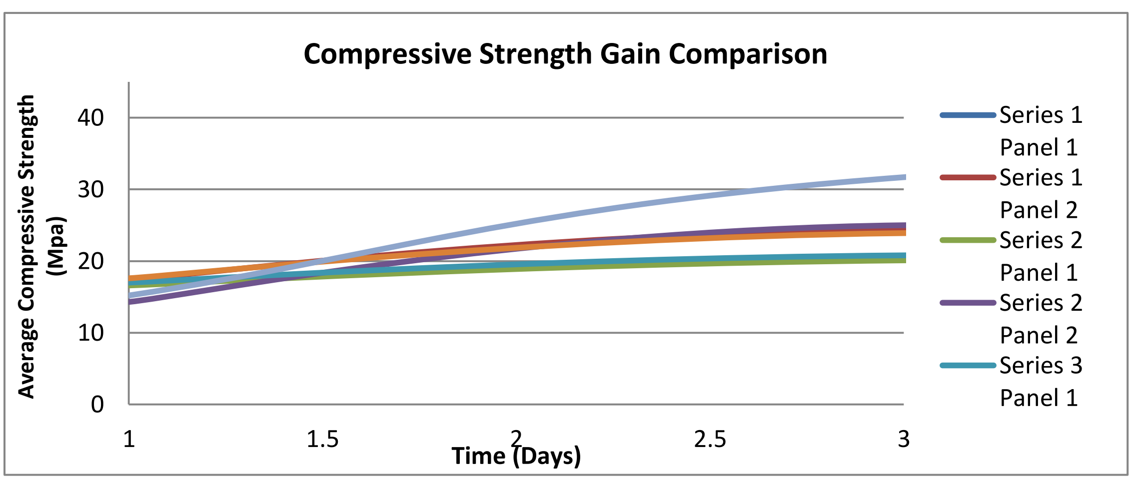

Figure 6: Compressive Strengths gained from the cored samples

From the above plots the difference between moulded cylinders and cored cylinder compressive strength can be observed, over a 3 day curing period. 1 day (24 hours) the compressive strength of cored cylinders was greater than that of moulded cylinders. The correlation of this data at 36 hours converges to below 8% variation. Kocevski (2011) also assessed both the temperature changes within the panel that were cored and a moulded cylinder control sample, where the Heat of Hydration within the cylinders reacted quicker than that of the panels and the compressive strength of the cylinders significantly surpasses the cored cylinder compressive strength. Kocevski (2011) concludes that the higher content of reactants in the panel, comparing the cored panel to the moulded cylinders, influenced the faster concrete compressive strength gains in the cored panels. From the results the lower compressive strength for the moulded cylinders can be attributed to slower Heat of Hydration reaction within the moulds, however cylinder compressive strength surpassed the cored cylinders at 72 hours by an average of 44%.

In figure 6, the comparison of moulded cylinders to cores (2 sizes 69mm and 110mm) suggest that there is no difference between the cored cylinders for either 69 and 110mm diameters.

4.2. In-direct splitting tensile test

A 40MPa and 20Mpa design strength panel mix was used in these tests.

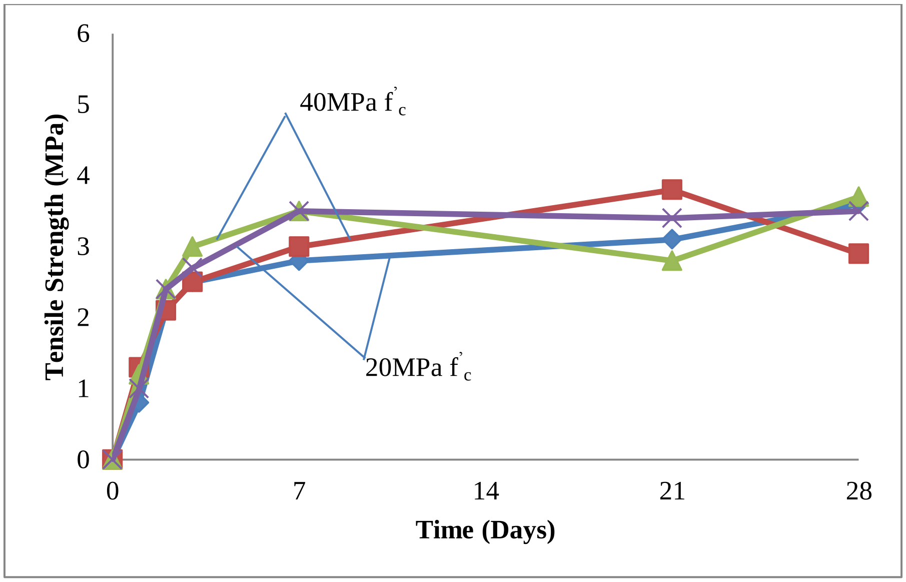

Figure 7: In-direct splitting test tensile strength results, 20MPa and 40MPa f'_c

Figure 7 shows a high variability within the 40MPa concrete mix where the tensile strength at 7 days and 28 days is less than the 3 day recorded strength of 3.4MPa. This shows a high variability within the Brazil cylinder compression tests.

The 20MPa concrete mix shows a rise over the 28 days curing, with the fastest gain in strength being within the first 3 days. The 50% gain in strength that was achieved between 7 days and 28 days. This may be explained through the high water to cement ratio and hydration continuing through 7 days within the concrete mix.

When assessing the splitting tensile test results, less than 3 days, the average f_{ct}, denoted in EQ1.2, is presented table 1.

Table 1: Calculated Uniaxial tensile strength, as per
$f_{ct} = 0.9\, f_{ct.sp}$

Age	f_{cm} for f'_c 40MPa	$f_{ct.sp}$	f_{ct}
1	9.4	1.9	1.71
2	28	2.6	2.34
3	33	3.4	3.06
7	43	3.2	2.88
21	50	3.5	3.15
28	50	3	2.7
Age	**f_{cm} for f'_c 20MPa**	**$f_{ct.sp}$**	**f_{ct}**
1	0.6	0.1	0.09
2	2.3	0.5	0.45
3	3.6	0.6	0.54
7	6.4	0.9	0.81
21	14.2	1.5	1.35
28	16	1.6	1.44

4.3. Uniaxial direct tensile tests,

There is no Australian Standard for direct tensile testing of this reduced diameter cylinder specimen, used in these tests. AS3600:2009 does however, recommend the use of:

$$f'_{ct} = 0.36\sqrt{f'_c}, \qquad \text{(EQ 4.1)}$$

Where:

f_{cm} was substituted for f'_c in the calculated values in table 2.

A relationship between the compressive and tensile for direct tensile testing proposed by Darwin et al. (1986) using EQ 1.3.

Table 2: Calculated f_{ct} values in accordance with EQ 1.1 and EQ 4.1 compared against tested f_{ct} values

Age	f_{cm} for f'_c 40MPa	EQ1.1 $0.36.\sqrt{f_{cm}}$	EQ 1.3 $g_t.\sqrt{(w_c \,.\, f_{cm})}$	f_{ct}
1	15.83	1.43	1.35	1.13
2	27.83	1.90	1.78	1.20
3	31.17	2.01	1.89	1.37
7	42.90	2.36	2.21	1.33
21	46.13	2.45	2.30	1.37
Age	**f_{cm} for f'_c 20MPa**	**EQ 1.1 $0.36.\sqrt{f_{cm}}$**	**EQ 1.3 $g_t \,.\, \sqrt{(w_c \,.\, f_{cm})}$**	**f_{ct}**
1	3.13	0.64	0.60	0.57
2	7.00	0.95	0.89	0.63

3	10.00	1.14	1.07	0.78
7	14.93	1.39	1.31	1.37
21	21.63	1.67	1.57	1.33

The measured tensile results, f_{ct}, are more conservative than the calculated values by both AS3600 (EQ 1.1) and Darwin (EQ 1.3).

4.4. Cast-in insert tensile tests

Each panel used a cast-in foot anchor which was placed at an embedment depth of 50mm. As this variable was kept constant, Figure 8 was graphed to emphasise the increase of the pull-out load over time for the 20MPa and 40MPa concrete mix. The predicted pull-out load was also graphed to illustrate the difference and show how the predicted pull-out capacities were conservative.

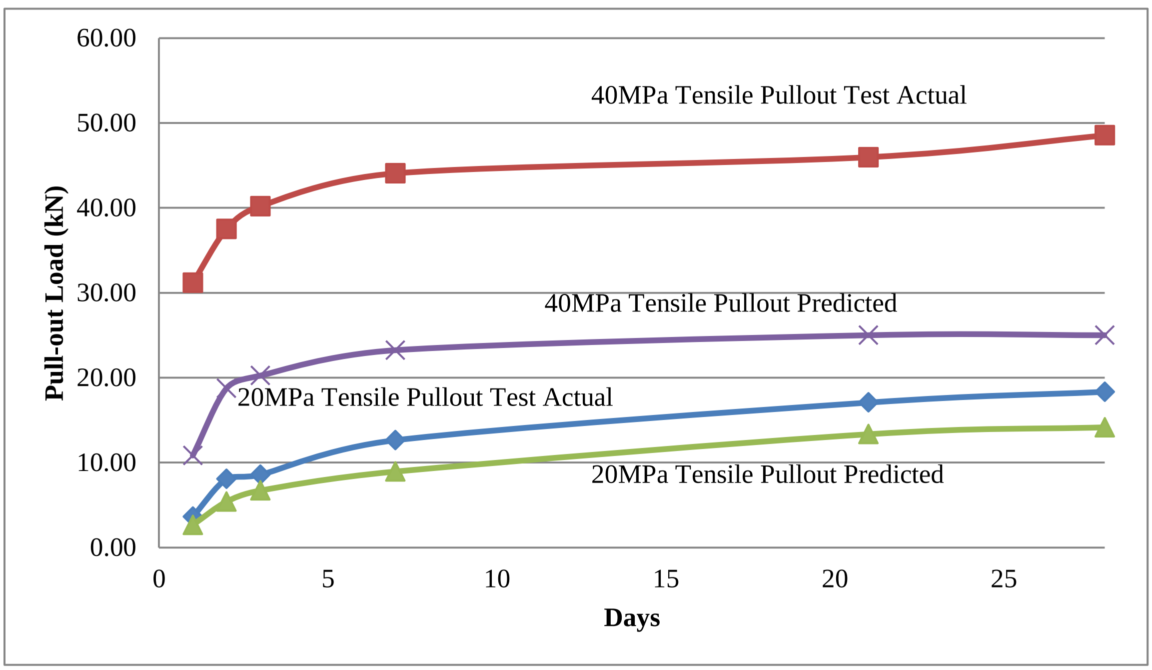

Figure 8: Comparison of calculated versus the mean actual pull-out ultimate load for a h_{ef} of 50mm in a 20MPa and 40MPa f'_c

The ultimate breakout capacity for a single anchor pull-out failure in tension with an edge distance not influencing pull-out has been expressed as (National Precast Concrete Association Australia 2009)

$$N_b = 10{h_{ef}}^{1.5}\sqrt{f'_c} \qquad \text{(EQ 4.2)}$$

Where,

h_{ef} = Anchor Embedment Depth (mm)

f'_c = Concrete Compressive Strength (MPa)

The calculation of unrestricted anchor tensile concrete pull-out is shown to be conservative for both concrete mixes used in these tests, and suitable for modelling.

5. Conclusion:

The strength variance at early age between coring locations was calculated for 24 hour old concrete by ANOVA testing. A 1% probability was achieved, showing the compressive strength varied due to coring location. This is lower than the specified significance level of 5%, surmises that at 1 day old concrete coring compressive cylinders differs depending on the location it was taken in the panel.

The test comparing the moulded cylinders against cored cylinders found that there was an average variance of 13% between moulded compression cylinders and cored compression cylinders at 1 day after pouring. The variance continued to increase over the 72 hour period and as such it is recommended that moulded compression cylinders be used over cored cylinders to establish the early age compressive strength.

The direct tensile test used in these tests is shown to be consistently conservative in comparison to calculated values from AS3600 and Darwin. The derivation of the models was from mature age concrete testing. Further testing to validate the test method used in this study for direct uniaxial tension testing is recommended.

Concrete at very early ages, less than 3 days, also showed higher than average pull-out results compared to what was predicted using the Concrete Capacity Design (CCD) method. The tests in this paper demonstrate that the model for the calculation of tensile pull-out in early concrete age is conservative and appropriate for lifting design.

Crack formation and fracture energy depend on the mechanical interaction between inclusions (mainly course aggregate) and the cement based matrix, is an area for further research to expand the current knowledge for tensile concrete capacity.

Recommendations for further research are to establish a numerical model that can be used to optimise concrete with well-defined parameters: strength, ductility, durability, fracture toughness and the way course aggregate influences concrete tensile capacity.

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