INVESTIGATING THE COMPRESSIVE STRENGTH OF CONCRETE COLUMNS CAST WITH A WEAKER INNER CORE

ABSTRACT

Under simple axial compression tests, the length to diameter ratio of concrete cylinders is kept small to prevent buckling. As it cannot buckle, increasing internal stress due to shortening of the cylinder develops triaxially rather than axially, and, as the same volume of concrete being forced to occupy a progressively smaller volume of space, an outward expansion of the cylinder occurs. Eventually, the confining strength of the cylinder is overcome, and it fails. Because overall failure is expected to be dictated by failure of the external concrete (i.e. the 'shell' of the member), it is theoretically possible that two cylinders with the same shell strengths but different core strengths could have similar compressive strengths. This project attempts to explore this idea by investigating the compressive strengths of concrete cylinders cast with a weaker inner core. Variations of core diameter, strength, and joint development (due to allowing setting times of shells before cores are filled) are all considered. Despite some difficulties in fabrication and testing, the results demonstrate fairly conclusive evidence of the legitimacy of the model put forward, and, in certain cases at least, that the importance of horizontal confinement of triaxial stress takes precedence over vertical stress resistance. The project aims to provide some groundwork for future experimentation that may provide a better understanding of the internal dynamics of concrete compression members, as well as possible industrial applications such as increased carbon sequestration in cores without affecting overall strength and fabrication of hollow columns confined by FRP sheets.

ACKNOWLEDGMENTS

First of all, I must acknowledge the Department of Civil Engineering at the University of Calgary for offering a senior undergraduate course that gives the opportunity for students to pursue independent research. I believe that the experience gained by myself and others who have chosen to take this course offers a unique opportunity for personal exploration, development, and independent thinking that cannot be gained from regular lectures and group projects. Second, I must thank Dr. Raafat El-Hacha for his constant support for this project and its rather unorthodox nature, as well as for his willingness to engage in many discussions about engineering and other important topics. Finally, as this project was entirely about making and testing concrete, I am grateful to fellow students who were willing to assist at times in lightening the load of fabricating the cylinders, but more importantly, the project would not have been possible without the support staff in the civil lab: Mirsad Berbic for his help fashioning the metal connections for the pi gauges, Don Anson for introducing me to the strain gauge software, and, most of all, Terry Quin for his interest in my project and subsequent suggestions and guidance, his supervision in the lab, and his constant patience with all my ideas, schemes, and... oversights.

TABLE OF CONTENTS

LIST OF TABLES AND FIGURES

Introduction

Euler-Bernoulli Theory

Many of the assumptions that are made in order to predict the performance of structural members are based on the Euler-Bernoulli theory of flexure. It states that because 'planar sections remain planar', curvature of a flexural member implies that the tension strands lengthen while compression strands shorten. The result is a linear stress distribution along the cross-section of the member, with maximal tensile and compressive stress occurring at the external tensile and compressive strands. It is from this framework that we derive the flexural formula $\sigma = My/I$

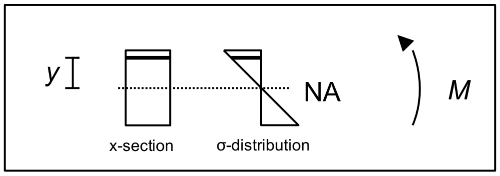


Diagram 1: Linear elastic stress distribution

where M is the moment about the neutral axis, y the distance from the neutral axis of the strand in question, and I the moment of inertia of the cross-section. This is valid as long as σ is below the yield stress of the material in question. Once the yield strength is exceeded, the member is no longer elastic and the external strands plasticize, forming a uniform distribution at the exterior that approaches the neutral axis as the stress is increased until the member becomes fully plastic and failure occurs.

Although the dynamics of compression members follow a similar theory in some ways, (as shortening of the member under an axial load implies some form of bending), there are certain aspects that are different. This is especially true in compression cylinders used for tests, as the height-to-diameter ratio is small to prevent buckling (wherein the member would behave like a flexural member), and instead of bending, there is a horizontal swelling of the cylinder due to the fact that its shortening implies that the same volume of concrete must occupy a smaller vertical space.

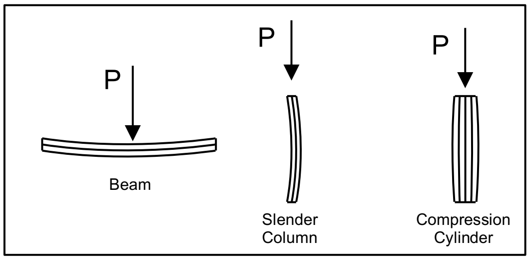


Diagram 2: Contrasting behaviour of beam, slender column, and cylinder under load P

Failure Mechanism Model

Because of this behaviour of compressive cylinders, the stress distribution over a cross-section is neither linear (as is the case of a slender column) nor uniform (as would be the case if no shortening occurred), and instead a triaxial state of stress takes place [1], wherein both horizontal and vertical stresses affect the internal layers. Due to the increase in stress and thereby the increase in horizontal stress as shortening increases, one expects that failure will occur when the confining strength of the external layer of the cylinder is overcome, either due to vertical compression or horizontal expansion. The implications of this mechanism is that failure would be governed not by the strength of the entire cylinder, but by an outer shell. In the theoretical characterization of the compression cylinder in Diagram 2, the central strands undergo little bending due to horizontal forces acting approximately equally in both directions, while the external fibre strands undergo maximum flexure due to the lack of confining horizontal stress external to them. If one takes external flexural failure as a governing mechanism, then it is possible to use the original Euler-Bernoulli model to predict the behaviour of the compressive cylinder, except that one only considers the linear tensile bending section below the neutral axis due to the observations that a) the compressive strands in the original model are now confined by the compressive strands of another symmetric 'beam' acting against it and b) concrete will fail far sooner in tension than in compression.

If the implications of this theoretical model are considered, then the difference between non-failure and failure can be modelled based on whether the resistant strength of the concrete lies inside or outside of a linear 'failure envelope' defined by the Euler-Bernoulli model assumed. If the concrete cylinder is made of two different strengths (hereafter referred to as a 'hybrid' cylinder) A > B, this implies that failure may not necessarily occur at the exterior as would be expected to occur from a homogeneous cylinder made of a single concrete strength. Diagram 3 demonstrates the manner in which the failure envelope and concrete strength are idealized. On the left side, the arrows represent the uniformly distributed resistance from each of the sections of the cylinder, while the right-sided linearly distributed arrows represent the stress distribution predicted by the aforementioned model. Failure is predicted to occur when the linear stress exceeds the uniform resistance.

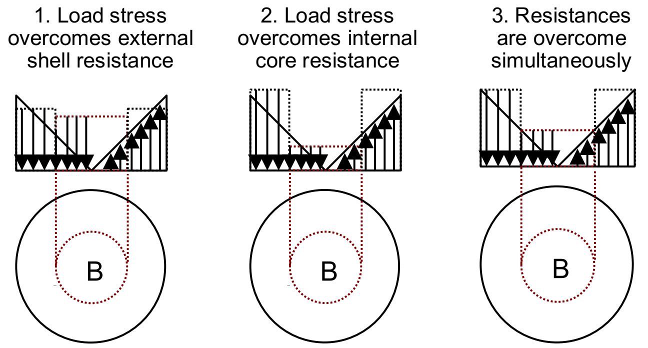


Diagram 3: Failure modes based on Euler-Bernoulli 'failure envelope' model

Diagram 3 shows three possibilities of failure when there are two concrete strengths. The mechanism of failure of the external core immediately after the internal core is expected to occur immediately in one of two ways: a) via a lack of *vertical resistance* to the applied load as a loss of resistance in the external core results in a decrease in resistance area and hence a proportional increase in the overall stress (= P/A) or b) via a lack of *horizontal constraint* to the horizontal forces, essentially resulting in the shell being prone to local buckling, and acting as a slender column rather than a compression cylinder, especially since tensile bending will have already occurred to some extent (see Diagram 2) and it has been well-established by e.g. Van Der Neut [2], [3], and Thomson and Lewis [4] that thin-walled compression members are especially prone to axis imperfections.

Predicted Failure Behaviour

Since within the project, results are based on relative strengths and diameters, the shell strengths will remain consistent at an expected strength of approximately 40MPa. When modelling the behaviour of the cores, there are two ways to increase the compressive strength of a cylinder. The first is to decrease the core diameter, thus allowing the higher shell strength to resist more of the linear stress. The second is to increase the strength of the inner core so that the core itself resists a higher stress. Based on the failure modes outlined in Diagram 3, it is expected that from the limiting case where the entire cylinder is of core strength, the overall strength of the cylinder should increase linearly either as the diameter increases — and thus the area of core failure decreases — or as the core strength increases — and thus the amount of stress that can be resisted increases — until it reaches a transition period where failure is no longer dictated by the core but by the shell. At this point, it is expected that the strength reaches a plateau and further increases in core strength or diameter will have no effect on the overall strength of the cylinder as failure is entirely dictated by the shell, which is limited by the stress at the exterior strand irrespective of the dynamics of the core. This is summarized in Diagrams 4 and 5, with a possible transitional drop-off (depicted in Diagram 5) due to the dynamics of the joint.

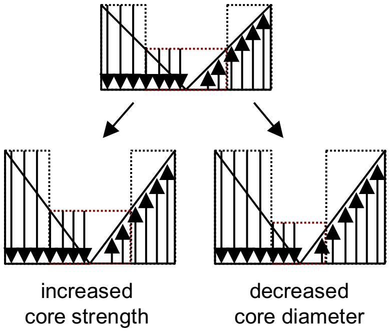


Diagram 4: Model-based effects of increasing core strength or decreasing column diameter

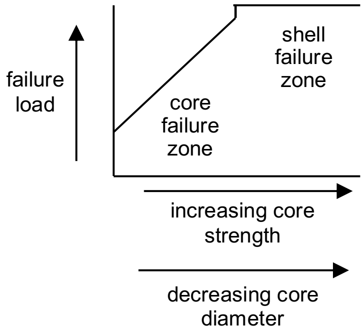


Diagram 5: Hypothesized failure dynamic

Overview of Project

The current project attempted to investigate to what extent the predictions of the aforementioned theoretical model would be realized in practice. In total, four batches were fabricated and tested. The first batch varied both diameter and strength simultaneously in order to establish whether *something* akin to the dynamic of the model might be at work; in addition it included hollow test cylinders to dispel the possibility that external shell failure is due to the core contributing nothing to the strength of the cylinder. Once the first batch established the likelihood of a behaviour that could be explained by the above model, the two subsequent batches were tested for the effects of changes in core diameter and strength. In addition, these batches allowed for different setting times in between shell and core casting, and the final test attempted to see not only if there was an effect on strength from allowing a set, but also to check the comparative consistency of doing overall strength tests on large (standard 150cm diameter x 300cm height) test cylinders, while testing the strengths of the individual concrete components with small (standard 100cmx200cm) reference cylinders (this will be explained further in the appropriate section). Details of each test, including details of the cylinders cast, a results section, an analysis and discussion of the results, and a short section discussing specific limitations and shortcomings are given in each individual section.

For the purposes of clarity, the report opens with a short preamble outlining common problems encountered in the fabrication and testing processes and the possible effects or lack thereof on the cited results. The main body begins with an overall description of the fabrication techniques as the casting of hybrid test cylinders is unusual and it is important to understand how the cylinders are made in order to better understand possible effects on compressive strength as well as to replicate the technique should further research be considered. It is hoped that the observations and results from these tests may be checked and/or expanded at some point in the future by myself or another interested party under more rigorously controlled conditions. To help facilitate this, at the end of the conclusion I have included several questions that I believe are important to answer in order to validate (or invalidate) the results contained herein.

Prelude to Results

As mentioned in the introduction, a number of difficulties occurred during this project. First and foremost is that as far as I could see, no such precedent occurs for fabricating hybrid cylinders, nor does there appear to exist any previous data to consider when setting out the current project. Thus, the setup and procedures of the experimentation is based entirely on the ideas of myself and those that I worked with. The second difficulty is that I was somewhat restricted in the materials available to me. At the outset, I had planned to try to 'hone in' on locating the transitional zone of an optimal core diameter/strength combination that would maximize the size of core while maintaining an overall strength as close as possible to the maximal (i.e. shell) cylinder strength. However, I only had access to a set of several discrete sizes of core moulds, so I could only test a limited number of diameters.

The third difficulty was a lack of time both in terms of the time that I could dedicate to the project and the availability of lab time for casting and testing, which meant that some problems consistently arose. At times there was a day between testing of the reference cylinders and the hybrid cylinders, and although this likely did not affect results too much, the rate of early strength gain may mean that there was a non-negligible strength gain in the intervening time. Also, in order to maximize my output in the lab, higher loading rates for the larger cylinders were employed. Fu, et al notes “Watstein (1953) suggested that there was on average an increase of over 80% for concrete loaded at a strain rate of 10/s, compared to that for concrete loaded at a strain rate of 10^{-6}/s. Based on available experimental data, Norris et al. (1959) developed design curves, giving strength increases of 33%, 24%, and 17% over static strength for strain rates of 3/s, 0.3/s, and 0.1/s.” [5] The result is that although Day concludes “within the range 20 to 100 MPa, the expected strength using 100-mm plastic or steel molds is 5% greater than if 150-mm plastic or steel molds are used” [6], it will be seen that in the present project the hybrid cylinders consistently perform better than the test cylinders, even when the concrete itself is seemingly identical (see Test 4). This lack of time also affected the installation of the strain gauges for the compression tests. As there was no strain/modulus apparatus for large cylinders, I used pi gauges whose ends were screwed into metal brackets glued to the cylinders. At times, the torque from screwing the gauges in dislodged the adhesive bond, rendering the gauge useless, but I did not have time to reapply the glue and the gauge, so many of the strain results are based on one the strain from one gauge rather than an average strain from multiple gauges. In general, because the more important results are largely comparative (i.e. between the hybrid cylinders) rather than absolute (i.e. the actual strength) these discrepancies did not have a particularly detrimental effect on the results.

Another recurring problem was maintaining the core mould in the middle of the cylinder (see below) during the fabrication process (detailed below), which would result in cores that were off-centre, affecting the symmetry of the model, and, likely, the symmetry of the strain. There were also difficulties with trying to keep the two sections separate, though Test 4 revealed that the actual outcome may be acceptable.

The final problem was that my inexperience with concrete meant that I was not always aware of problems that might arise and how to fix them and/or which aspects of fabrication I could and could not ignore without adversely affecting my results. Given these shortcomings, it is important to re-test any results contained herein before coming to major conclusions.

10/15/2014

Photo depicting asymmetric core

Experimental Methods

Casting

As this project involves testing concrete, casting is, of course, very important. In the case of this particular project, it is even more important as the casting process is not straightforward. In order to cast the cylinders, it is necessary to partition the cylinder during casting. What is more, in order to be able to test diameter sizes that are disparate enough to provide results that cannot be put down to casting or experimental error, it is necessary to use the larger standard test cylinders, whilst it was deemed sufficient (and conservative in terms of concrete use and time required for testing) to use the smaller cylinders to test individual concrete strengths. Moulds were ~18” ABS pipe lengths with outside diameters of 48mm [referred to hereafter as 2”], 60mm [2.5”], 89mm [3.5”], 114mm [4.5”]. The casting process was as follows:

1. Batches of pre-tested concrete recipes were chosen based on desired strengths
2. Desired volumes were calculated with an additional 10% waste
3. Volumes larger than $0.03m^3$ were prepared in a mechanical mixer, smaller volumes were hand-mixed in a wheelbarrow
4. Cylinders were prepared, pipe sections were placed inside the large cylinders, centred by measuring a constant distance between the pipe and the cylinder with a ruler
5. Shell concrete batch was mixed first and shells were filled around pipe along with reference cylinders, with compacting done via tapping on cylinders and vibrating at approximately half volume, filled shells were then trowelled with a blade and left for initial set (if applicable)
6. Core concrete batches were mixed and cores were filled approximately halfway, compacted by rodding and tapping on cylinder
7. Pipes were slowly extricated while rodding cores, core concrete was topped up as needed
8. When pipe was fully extricated and cores were filled and rodded, cylinders were troweled and left to set; reference cylinders were prepared, vibrating at approximately half full and full
9. Concrete was extracted from moulds the following day, and grinding of cylinders was done within the next few days to prepare for testing

Testing

An Amsler compression machine hooked up to a digital readout was used for all compression tests. The smaller reference cylinders were tested without strain measurements, while the larger test cylinders (except in Test 1) were tested for strain. To measure strain, metal brackets were affixed to the cylinders with epoxy, and when tested, PI-5-50 Displacement Transducers (pi gauges) were screwed into the metal brackets. The gauges were connected to a computer, and the program Build Time was used to collect strain readouts at a rate of 1 per second.

PI-5-50 Displacement Transducer Gauge

Amsler Compression Machine

Test 1: The Hypothesis Test

Methodology

This preliminary test was conducted in order to see if something that resembled the hypothetical model might be at work and whether to pursue the project further. In addition, it was used to test whether the fabrication process would work or not. Hollow cores were tested to make certain that test results could not be attributed to shell strength as a whole (i.e. that the core does contribute to the overall strength of the member). The pipe moulds that were used for this original test consisted of whatever could be found around the shop, thus a metal pipe of diameter 2 7/8” was used in this first test before materials were purchased to standardized the core sizes. Nine concrete members with shells of strength ~40MPa (A) were tested, three of which contained ~30MPa cores (B), three of which contained ~20MPa cores (C), and the remaining three remaining unfilled (i.e. hollow). Each of the three types of cores had diameters of 2.5”, 2 7/8” [74mm], and 4.5”. No initial set was allowed: cores were poured immediately, and one pipe was used repeatedly for each size cylinder. The pipes were left inside the hollow cores and an initial set of approximately two hours was allowed before the pipes were extracted.

Results

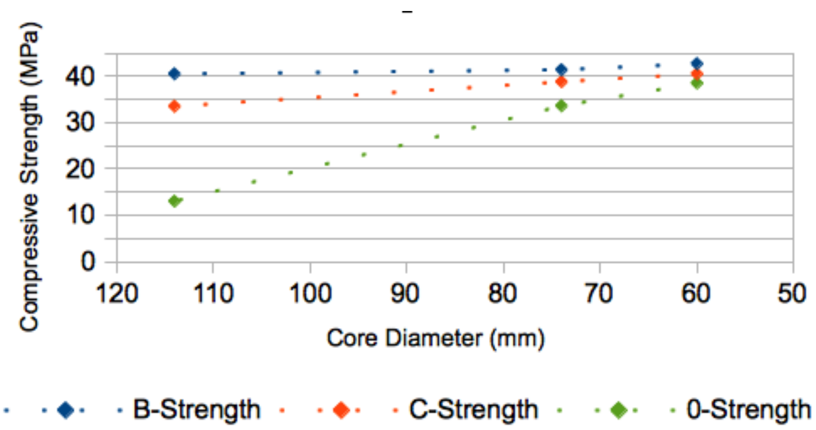
No strain gauge was used for this test. Peak loads (kN) were found, compressive strengths (MPa) calculated and results were simply checked for possible correlation with the model.

Table 1: Test 1 Results

Core Type	2” Peak load; Strength	2 7/8”	4.5”
B	806.78; 42.7	782.19; 41.4	764.08; 40.5
C	764.64; 40.5	732.89; 38.8	633.51; 33.6
Hollow*	727.86; 43.2 (38.5*)	631.50; 43.0 (33.5*)	244.37; 28.2 (13.0*)

*These strengths (used in Graph 1) are based on enclosed area, i.e it has a core strength of 0 MPa

Reference cylinder average strengths: A: 38.2MPa; B: 30.9MPa; C: 24.4MPa



Graph 1: Test 1 Compressive Strength vs Core Diameter

Analysis and Discussion

We can note first of all that if we consider the hollow cores as 'zero-strength', it is evident that there is a disparity between the hollow shells and the filled shells, and thus that the core does contribute some strength to the overall member. This is especially true for the thinnest shell: in comparison to the filled shells, there is a very large drop-off of overall strength, seemingly implying that as the shell gets smaller, the strength contribution of the core is more important, an effect explainable by the mechanism that would attribute failure to local buckling. In addition, by comparing the relative strengths between cylinders, we see that the disparity between overall strengths increases as the shell size decreases: when the shell is large, the overall strengths are fairly close together, while as the shell size decreases, the disparity between overall strengths grows. Although it is not clear whether or not that there is a plateau and transition phase as predicted by the model, it seems fairly safe to say that there is sufficient evidence to imply at this point that the model cannot be rejected.

Shortcomings

As this was the initial test, it was also the first attempt to test an as yet untried fabrication process. The major experimental error with this original batch was that I had been so focused on making sure the fabrication process went smoothly that I had forgotten to properly oil the cylinders (both large and small), and thus the extracted cylinders had a lot of damage around the bottoms (the contact surface with the cylindrical moulds), leading to most of them having to be capped, likely affecting the results in some way. In addition, it was fairly evident during the fabrication process that keeping the pipe moulds still and centred would take some practice (as evinced by the photo of the uncentered hollow core in the prelude section), and that workability issues might enter into the equation for the smallest of the cores (2”) and the thinnest of the shells (4.5”). Further, because only one of each sample was tested, it is not possible to check the consistency of the samples, and whether or not the results are simply a matter of samples performing better or poorer than an average.

Test 2: The Diameter Test

Methodology

With the first test having shown some evidence for the validity of the model, this test was designed to check the effect of core diameter on the overall strength of the member. The fabrication process was also variedallow for an initial set of approximately one hour to see if the core-shell interface might be better stabilized during the process of extracting the pipe to pour the centres (as the shells would have some amount of rigidity at this point), yet it was felt that it would not be wise to allow an actually cold joint to form (equivalent to filling the hollow cores that were fashioned in Test 1). Also, in order to check for some level of consistency of results, two members of each size were made. In total, eight large cylinders were made of ~40MPa shells and ~25MPa cores, two of each diameter size (2”, 2.5”, 3.5”, 4.5”) along with three reference cylinders of each strength.

Results

Strain gauges were installed as described in the testing section, and where all tests where gauges slipped, allowing only one reading and not an average, are noted. Peak loads (kN) were found, compressive strengths (MPa) calculated and results compiled. The theoretical values are calculated in two ways. The bracketed value is a simple weighted average using the absolute strengths of the test cylinders and contact areas using the outer diameter's values for the pipes and an approximate mean cylinder diameter of 151.8mm (as getting an exact mean value is of little importance). The other value is a relative weighted average based on the model. It gives the shell concrete strength to be equivalent to the average of the peak strength of the cylinder with the smallest diameter (assumed by the model to be closest to the strength of the shell concrete), and then uses a core strength value proportional to the ratio between the average test cylinder strengths. This tries to compensate for the discrepancies in test cylinder value and to better evince the relative strengths of the cylinders.

Table 2: Test 2 Results

Test Cylinder Values

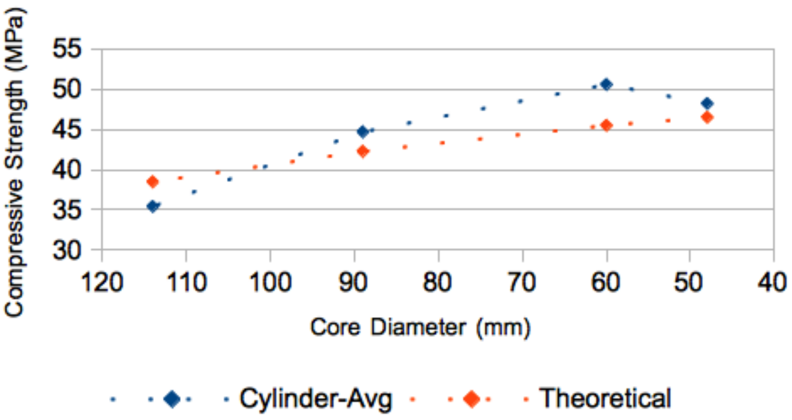
Sample	Peak Load (kN)	Peak Strength (MPa)	Theoretical* Peak Load (kN)	Theoretical* Peak Strength (MPa)	Theoretical* Increase (%)
2”(1)	869.59	48.07	840.96 (765.32)	46.47 (42.29)	3.4 (13.7)
2”(2)	874.74	48.31	840.96 (765.32)	46.47 (42.29)	4.0 (14.2)
2.5”(1)	920.04	50.76	823.45 (749.38)	45.50 (41.41)	11.6 (22.6)
2.5”(2)	911.79	50.36	823.45 (749.38)	45.50 (41.41)	10.7 (21.6)
3.5”(1)	826.62	45.60	765.05 (696.23)	42.29 (38.49)	7.8 (18.5)
3.5”(2)	791.74	43.75	765.05 (696.23)	42.29 (38.49)	3.5 (13.7)
4.5”(1)	637.60	35.21	696.91 (634.23)	38.48 (35.02)	-8.5 (0.5)
4.5”(2)	645.54	35.64	696.91 (634.23)	38.48 (35.02)	-7.4 (1.8)

Reference Cylinder Values

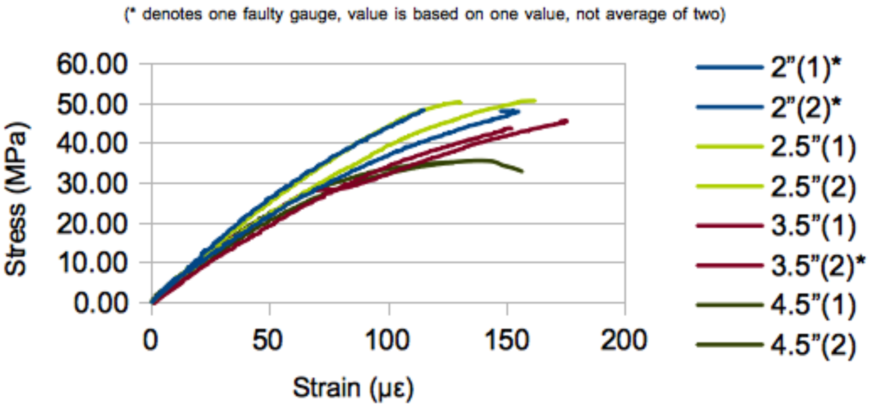
	Cylinder 1 (MPa/kN)	Cylinder 2	Cylinder 3	Average

~25 MPa	29.67 (241.57)	27.01 (220.40)	27.92 (227.39)	28.20
~40 MPa	42.57 (346.32)	46.45 (377.85)	42.53 (345.99)	43.85

Graph 2: Test 2 Compressive Strength vs Core Diameter



Graph 3: Test 2 Stress-Strain Curves



Analysis and Discussion

Looking at the data values in Table 2, it is immediately evident that there is an anomaly in the data. It is unlikely, given the behaviour of concrete, that an increase in core diameter should result in an *increase* in overall strength. As both of the 2” and 2.5” cylinders are close in strength to each other, and have some disparity between them, it is unlikely that the error can be attributed to the testing procedure. The most plausible explanation is that there was a problem with the fabrication process, and given the closeness of the test results, it is assumed that it was a systematic error. Given that the inner diameter of the 2” pipe mould was a mere 40mm, and that it was difficult to fill it, there may have been workability issues. Although the model assumes that the core's contribution to the strength should be limited, it is possible that the shell was disrupted during the rodding because of the small cross-sectional area, affecting the strength of the outer shell. This would also imply that using the 2” cylinder strength as the reference value for calculating the theoretical values would underestimate the theoretical strengths.

The above anomaly aside, Graph 2 implies that the relative strengths relatively stable (lying above the theoretical line), and then drops off. The slope of the line between 2.5” and 3.5” is 0.20, while that between 3.5” and 4.5” is 0.37. If a linear drop-off is assumed after the transitional phase and there is no transitional drop off, it would imply that the transitional phase should exist somewhere between 2.5” and 3.5”. This can be estimated by extrapolating the line with slope 0.37 to the approximate peak strength of 50MPa, resulting in an estimated transitional diameter of 75mm, approximately 2 7/8”. It may be interesting to see what strengths would result from testing at that diameter.

One thing to note from the stress-strain curves is that the behaviour of the two cylinders of larger core diameter appear fairly consistent, whereas both of the smaller cores do not, and this is consistent when considering only the cores where averages could be taken (2.5” and 4.5”). One possible explanation is that it is easier to keep the pipe moulds centred when they are larger both due to the larger surface area of contact, and the increased ease with which one can estimate the centering of the larger moulds in the cylinder (recall the photo of the highly uncentered hollow 2.5” core). If a core is asymmetric, one expects strain effects to also be asymmetric and therefore more prone to non-uniform behaviour. On the other hand, it is also interesting to note that the only curve with an appreciable drop-off is the one at 4.5”, the one where failure seems undoubtedly dictated by core failure. It may be plausible that the strain is likely to be more pronounced in weaker concrete as the resistance to crushing would be reduced, however Nielsen and Hoang caution against this, providing several reasons for concluding “it does not seem worthwhile to draw too many conclusions on the basis of one type of measurement of the descending branch [of a stress-strain curve]” [4]. Yet under the special conditions of this project, it is expected that an internal core failure would cause overall failure due to a rapid increase in the stress having to be resisted by the shell alone. This could explain the curve behaviour.

Shortcomings

Other than the systematic problems associated with gauges, reference cylinder strengths (and, in this case, their large strength disparity), fabrication anomalies, etc., the main issue with this test (and others) is that a larger subset of data is required to reach any definitive conclusions. With only two samples, it is not possible to check for statistical significance via ANOVA or similar tests. However, given that this is a rudimentary experiment, the inferences from applying the model to the present data seem to demonstrate at least some degree of plausibility.

Test 3: The Strength Test

Methodology

This third test attempted to investigate the correlation between core strength and overall strength while relating it in a limited manner to diameter. It was also decided to experiment further with the fabrication process to allow for an initial set of approximately 2 hours to see if the core-shell interface could be further stabilized and/or if any noticeable anomalies might be seen due to shearing along the joint. Again, for consistency, two members of each size were made of each diameter/strength combination. In total, twelve large cylinders were made of ~40MPa shells. It was intended that the strengths would have a reasonable amount of disparity, so three batches, one each of ~15, 25, and 32MPa core concrete were mixed, and four cylinders, two each of core sizes 2.5 and 3.5” were made for each strength. However, it ended up being the case that there was insufficient water for the small batches. My inexperience caused me to overcompensate on water greatly for the first batch, less so for the second (but both requiring the further addition of fine aggregate to reach a reasonable degree of consistency), and slightly for the third (which required no further aggregate addition). Thus, the reference cylinders ended up with average strengths of ~7, 17, and 26 MPa (though this relative disparity suited the purposes of the experiment just fine and resulted in some interesting findings), and the low strength cylinders had to be capped as they were too weak to grind properly.

Results

The results of this test were compiled according to the same methodology of Test 2, with theoretical peak loads again based on a weighted average from the assumed strength of the shell concrete given by the value of 45.26, the average of all of the 2.5" cores, which have similar overall strengths.

Table 3: Test 3 Results

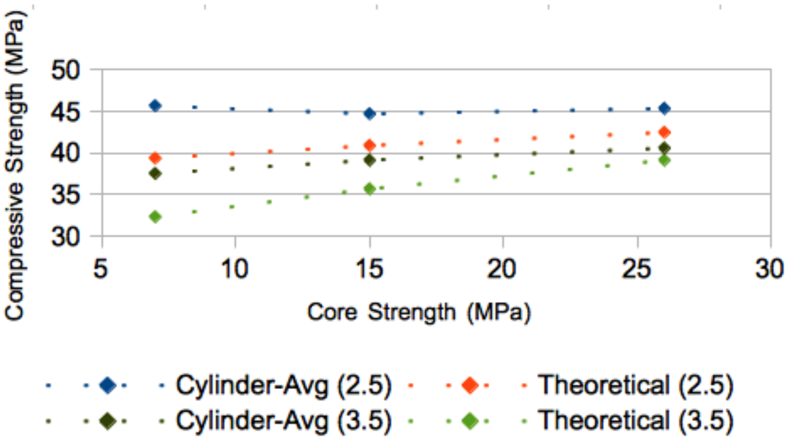
Test Cylinder Values

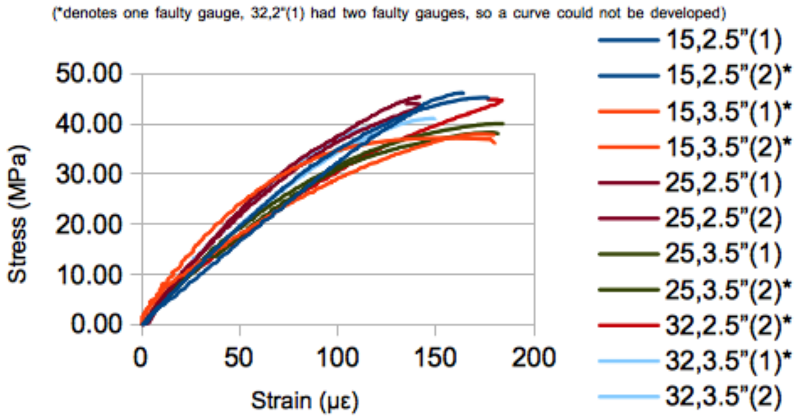
Sample	Peak Load (kN)	Peak Strength (MPa)	Theoretical* Peak Load (kN)	Theoretical* Peak Strength (MPa)	Theoretical* Increase (%)
26, 2.5"(1)	831.60	45.88	769.28 (733.04)	42.48 (40.48)	8.0 (13.3)
26, 2.5"(2)	813.07	44.86	769.28 (733.04)	42.48 (40.48)	5.6 (10.8)
15, 2.5"(1)	796.41	44.03	740.81 (705.91)	40.91 (38.98)	7.6 (13.0)
15, 2.5"(2)	822.73	45.40	740.81 (705.91)	40.91 (38.98)	11.0 (16.5)
7, 2.5"(1)	819.15	45.23	713.13 (679.54)	39.38 (37.53)	14.9 (20.5)
7, 2.5"(2)	835.34	46.16	713.13 (679.54)	39.38 (37.53)	17.2 (23.0)
26, 3.5"(1)	725.57	40.10	708.95 (675.55)	39.15 (37.31)	2.4 (7.5)
26, 3.5"(2)	744.88	41.09	708.95 (675.55)	39.15 (37.31)	5.0 (10.1)
15, 3.5"(1)	724.64	40.02	646.30 (615.85)	35.69 (34.01)	12.1 (17.7)
15, 3.5"(2)	693.65	38.27	646.30 (615.85)	35.69 (34.01)	7.2 (12.5)
7, 3.5"(1)	686.33	37.91	585.40 (557.82)	32.33 (30.81)	17.3 (23.0)
7, 3.5"(2)	673.56	37.18	585.40 (557.82)	32.33 (30.81)	15.0 (20.7)

Reference Cylinder Values

	Cylinder 1	Cylinder 2	Cylinder 3	Cylinder 4	Average
~7 MPa	7.41 (60.25)	6.80 (55.33)	7.17 (58.35)	7.67 (62.37)	7.26
~17 MPa	16.77 (136.38)	16.61 (135.15)	16.20 (131.80)	16.78 (136.49)	16.59
~26 MPa	28.13 (228.83)	26.03 (211.73)	27.35 (222.46)	23.34 (189.03)	26.19
~40 MPa	47.33 (385.00)	38.85 (316.03)	40.95 (333.13)	45.38 (369.13)	43.13

Graph 4: Test 3 Compressive Strength vs Core Strength




(*denotes one faulty gauge, 32,2"(1) had two faulty gauges, so a curve could not be developed)

Graph 5: Test 3 Stress-Strain Curves

Analysis and Discussion

The first thing that is clear from the results is that a linear stress model that would attribute failure only to a lack of vertical resistance must be rejected. Despite reducing the strength of the core to a mere 7MPa, the strength of the cylinder with a 2.5” core remained at the strength of the other cylinders of the same diameter, while in the case of the 3.5” cores, the overall strength fell off in an approximately linear fashion, almost identical to the linear behaviour of the theoretical curves, though with different slopes, the disparity between the theoretical values increasing as the strength decreased. This seems to imply that the dominant attribute for cylinder strength is horizontal confinement of the shell rather than vertical resistance to stress. Noting this, if one was to fill the hollow cylinders from Test 1 with a bag of loose sand or replace all core cement with fly ash, how would it affect the strength? This has interesting implications for hollow-cored columns. For example, lining the centre with a material that is very strong in tension — such as a fibre-reinforced polymer (FRP) sheet — may provide a very large increase in strength while reducing the self-weight and material output (this will be discussed further at the end of the report, under "Summary of Results"). This test in particular seems to provide very clear evidence of a major disparity between shell and core failure dynamics of short columns, and may be exploitable to increase column strength or to reduce material output (e.g. fly ash for cement).


Photo depicting ruptured cylinder

An interesting side note is that although the test cylinders were not deliberately brought to failure, one cylinder — 15MPa 2.5" (2) — ruptured almost immediately after the peak load was reached and before the load could be removed. It can be seen from the photo on the right that the core is indeed intact, while the shell has taken the entire extent of the damage. This is further evidence that the core-shell failure model is indeed accurate. One can note that the top has probably remained intact due to the contact with the load plate, while following the diagonal of the failure interface, it stops at the core and continues along the joint to the bottom of the member. It is not clear whether it is the joint itself that explains this behaviour or if the two hour set differential between the sections contributes to the fact that the failure crack does not penetrate into the central core of the member. Although further testing of joint dynamics was tested in Test 4, other variables contributed to the test not being completely reliable. Joint dynamics should be tested further.

Observing the stress-strain curve, it can be seen that the results are consistent with the observation from Test 2. The rate at which the curves fall off for all of the 3.5" cylinders where core failure dictates overall failure is markedly higher than those of the 2.5" cylinders. There are inconsistencies, for example the two 15, 3.5" cylinders. However, as both relied only on one gauge, it is possible that differential strain is to be blamed for the divergence in strain development, though the final position of both stress-strain curves is consistent. In general, the pairs of curves are generally consistent in strain development, implying that the dynamics in the column should be repeatable under controlled conditions of fabrication.

Shortcomings

Although the core strengths were intended to be much higher, the mistake in batch preparation and resultant low strengths of the cores turned out to be a blessing in disguise, as it provides almost irrefutable evidence of a pattern to the internal dynamics of hybrid concrete cylinders, namely that core strength is only important when core failure dictates member failure, as the resistance to the core stress is what governs the cylinder failure. Other shortcomings, such as gauge problems, number of members to establish statistical relevance, etc. have already been discussed.

Test 4: The Joint Test

Methodology

The last test was intended to see how the joint conditions might affect overall strength. When cores are poured immediately after shells, one might expect that there will be a limited effect on strength given that setting of the layers will occur at the same time and some interaction of water, cement, etc. will occur, though it is not known whether allowing layers with differential setting to interact might create internal stresses. On the other hand, allowing some initial setting allows for easier pouring of the cores (as the slight structural integrity reduces the interaction). However, the longer the internal set, the more it is possible that the joint might invite extra cracking or shearing at or near it. This test was also used to substantiate that the testing procedures have caused the large cylinders to have higher strengths than the small cylinders: a 40MPa shell with a 40MPa core poured immediately after it should result in a similar strength to a 40MPa reference cylinder. If it is noticeably higher, it is likely that there is a systematic incompatibility between the two testing procedures. In addition, the concrete used for the cores is dyed red before pouring so that the cylinders can be cut apart after testing and their cross-sections observed to check on the extent of core consistency and/or bleeding between the layers. Eight shells of ~40MPa core were cast. Four of the (dyed) cores, two each of ~40 MPa and ~25MPa, were poured immediately after the shells (0t), while the other four (again, two each of ~40MPa and ~25MPa) were poured approximately 1.5 hours after (1t). One of each pair of the cylinders had a 2.5" core, and the other a 3.5" core. In order to reduce concrete waste, the same batches were used at both time points. The intention to use superplasticizer was rendered superfluous when the dye (normal paint dye purchased from a hardware store) was added to the concrete and seemed to have superplasticizing effects. However, when the second set of cores were eventually poured, workability became a serious problem, and so the actual effect of the joint on strength cannot really be determined, as workability issues are likely to play a role. Three reference cylinders were poured for each set, except for the 40MPa batch at 1t, as there was insufficient volume left. Given the overlap of 25MPa strengths between the two times, it was assumed that the 40MPa strength would also be similar.

Results

The results of this test were compiled according to the same methodology of Test 2. The adjusted weighted average value takes the 40MPa strength as the average of the two 40MPa, 0t cylinders.

Table 4: Test 4 Results

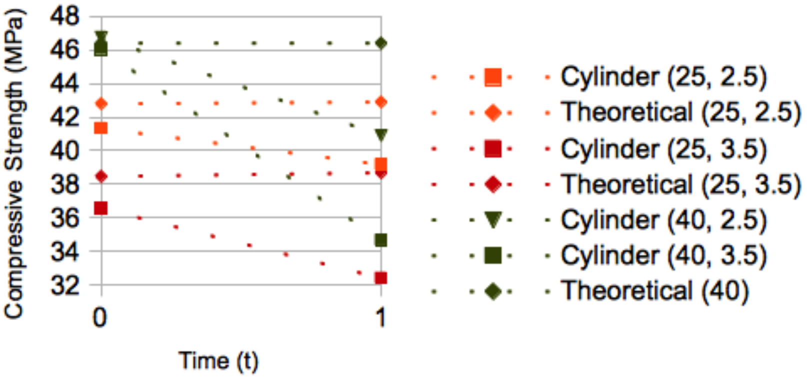
Test Cylinder Values

Sample	Peak Load (kN)	Peak Strength (MPa)	Theoretical* Peak Load (kN)	Theoretical* Peak Strength (MPa)	Theoretical* Increase (%)
25, 2.5", 0t	747.83	41.33	774.86 (694.60)	42.79 (38.36)	-3.4 (7.7)
25, 2.5", 1t	709.38	39.16	776.65 (696.20)	42.89 (38.45)	-8.7 (1.8)
40, 2.5", 0t	846.24	46.76	840.21 (753.17)	46.40 (41.59)	N/A (12.4)
40, 2.5", 1t	740.36	40.90	840.21 (753.17)	46.40 (41.59)	-11.8 (-1.7)
25, 3.5", 0t	662.20	36.56	696.44 (624.30)	38.46 (34.48)	-5.3 (-4.9)
25, 3.5", 1t	586.53	32.40	700.38 (624.82)	38.68 (34.51)	-16.2 (-6.1)
40, 3.5", 0t	833.63	46.04	840.21 (753.17)	46.40 (41.59)	N/A (10.7)
40, 3.5", 1t	627.48	34.66	840.21 (753.17)	46.40 (41.59)	-25.3 (-16.7)

Reference Cylinder Values

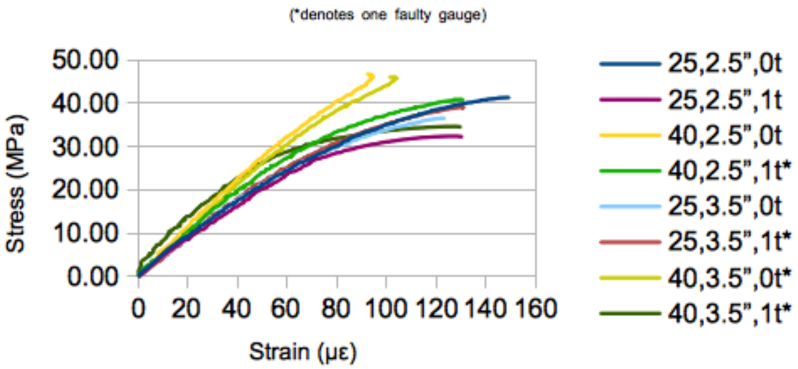
	Cylinder 1	Cylinder 2	Cylinder 3	Average

25 MPa (0t)	21.12 (171.93)	21.19 (172.71)	20.28 (164.89)	20.86
25 MPa (1t)	22.20 (180.76)	19.66 (160.30)	22.38 (182.32)	21.41
40 MPa (0t)	42.50 (345.31)	40.93 (333.13)	41.38 (336.59)	41.60



Graph 6: Test 4 Compressive Strength vs Joint Setting Time

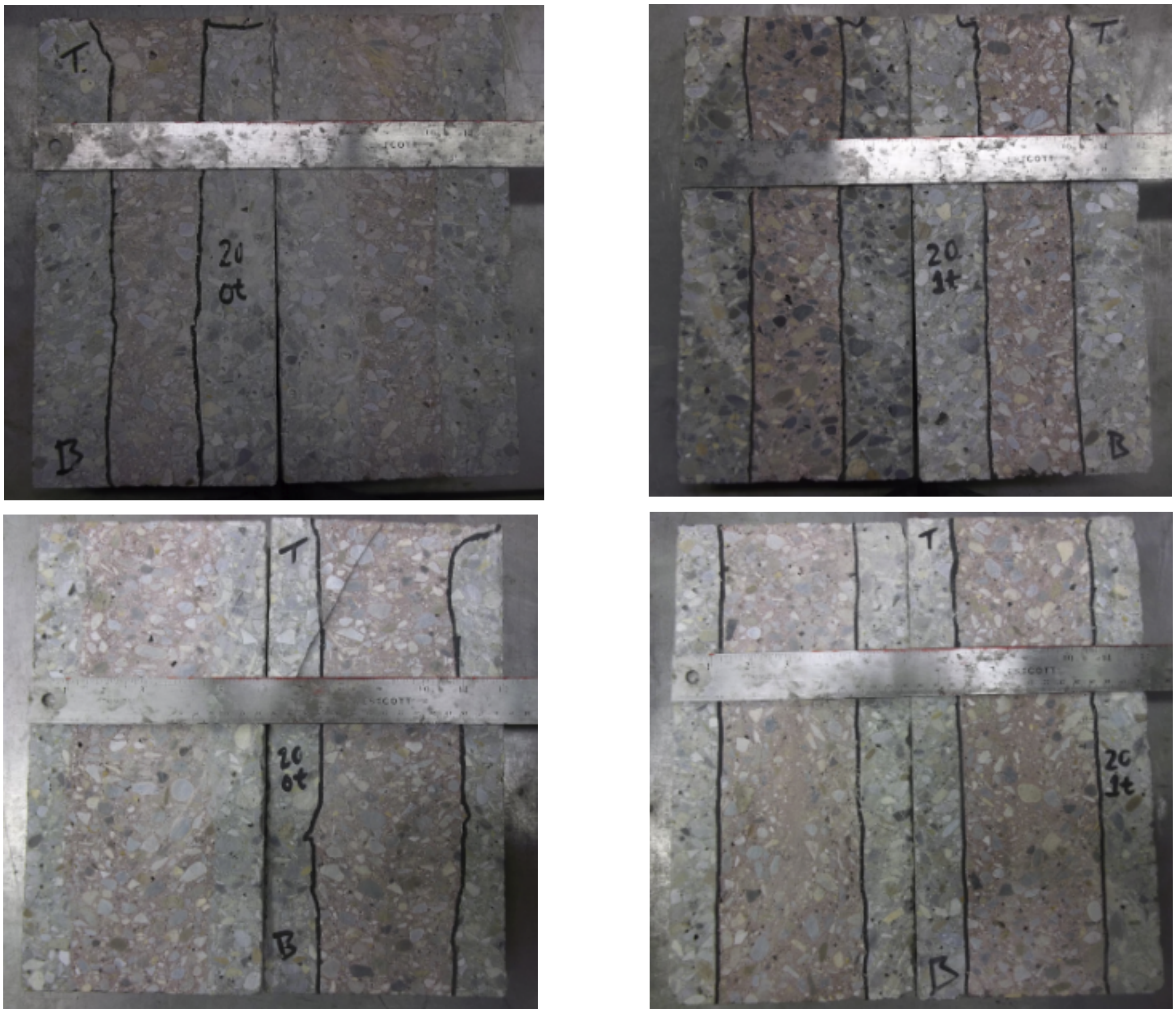
Graph 7: Test 4 Stress-Strain Curves


(*denotes one faulty gauge)

Analysis and Discussion

As mentioned in the methodology section, workability issues likely play a role in the results of this test. In addition, there is no need to provide an estimate of the shell strength concrete, as two 40MPa large cylinders were tests with similar peak values. Thus, the 'theoretical increase' values for the two 40 0t samples represent the disparity in strength between the two testing methods. The workability of the 40MPa concrete was severely affected by the time the 1t cylinders were poured, which explains the very poor performance of the 40 1t cylinders, noting especially that the 40 1t 3.5" cylinder actually performed worse than the 25 0t 3.5" cylinder despite core failures in both cases. This is further evidence that the lower showing of the 2" cylinders in Test 2 were affected by workability issues. In addition, in combination with the findings of Test 3, although a strength loss in the core should not adversely affect the member strength, the highly unworkable concrete did not pack together well, likely leaving gaps and disrupting the horizontal confinement of the shell, further evidence of the importance of proper shell confinement. However, the 25 0t cylinder would not have any workability issues and tested below the theoretical value when using the large cylinder strengths, but above the small cylinder strengths, implying that it was wise to check this discrepancy between the two testing methods, and that the absolute strength values throughout the tests may be called into question (though this does not severely influence the overall results from the project, as the emphasis is on comparative aspects). Moreover, the fact that both 25 0t cylinders performed appreciably below the theoretical value may imply that a correction factor would have to be used to account for the behaviour of the joint.

The stress-strain curves show a similar pattern to the previous tests. However, what is interesting to note is that all stress-strain curves other than the 40 0t cylinders are quite similar and involve some overlap, implying that the effects on stress-strain behaviour may be more dependent on the differential set than the presence of a joint, since the division between the sections in the 40 0t cylinders were just as pronounced as that in the other cylinders.



Photos depicting 2.5” and 3.5” 25MPa cylinder cross-sections at 0t and 1t (T = top, B = bottom)

Of greater interest in this test is that of the core profiles (above). It can be seen that both of the 2.5” cores have well-established profiles, while of the 3.5” cores, the 0t specimen has an irregular bleeding at some places in comparison with the 1t specimen. It stands to reason that with proper fabrication techniques, allowing an initial set may not be so crucial for a well-partitioned member. However, it may be that the larger cores are harder to control than the smaller ones because there is more concrete present and a greater room for error. In addition, the larger volume of concrete also means that there is a larger total downward force in the concrete, providing a greater impetus for the core to bloat outward, though the fact that the bottom of the one problematic cylinder has a well-established profile even though the force there should be the greatest may rule that out. Further, a cursory glance gives no evidence that there is a lack of consistency (noticeable gaps, unevenly distributed coarse aggregate, etc.) in the 1t cores due to workability problems.

Shortcomings

It has been mentioned that the workability issues that came with choosing to let the concrete sit out likely had a major effect on the strengths of the 1t members. On the other hand, the seemingly large effect of these problems leads one to believe that workability issues must be taken into account when fabricating hybrid cylinders, and thus columns with very small cores might be substandard. Other than this, it is noted that because only one cylinder of each type was fashioned, there is no way to check the consistency of the results.

Summary of Results

Considering the tests as a whole, and with the various errors and problems in the tests taken into account, there seems fairly good evidence that the model put forward is accurate to some degree. In Tests 2 and 3 (and to a small extent 1), showed the hypothesized plateau/transition/linear behaviour. Further, the findings of Test 3 seem to discredit the notion that vertical resistance of the core is at all important once in the shell failure zone, and that it may not be necessary to have any vertical resistance in the core so long as the interior of the shell has something to horizontally confine it and prevent it from internal expansion/flexure. As mentioned earlier, this could be tested by filling a hollow core with a material that is generally incompressible (e.g. sand or 100% fly-ash concrete, but not styrofoam) and seeing how it affects the overall strength of the member. The implications of this would be that a material with high tensile strength, such as an FRP sheet, could be used for internal shell confinement in place of filling the shell at all, reducing self-weight and material. Because FRPs are generally weak in compression, however, it might be wise to design such a member with a sheet that is slightly shorter than the member in order to take into account shortening of the member under compression in order that the FRP would not be damaged by taking on a portion of the compression load.

Although the core strength/diameter dynamics are now better understood, it is still necessary to get a better idea of the joint dynamics in order to decide on the ideal fabrication method. It may be that allowing for an initial set allows for better performance due to a more consistent core profile even though the sections may not interact as well. On the other hand, it may be preferable that there is reduced interaction between the shell and the core if internal stresses were to develop due to unequal setting dynamics between them.

Throughout all of the tests, the shell strength was kept consistent. Although one might be able to make certain educated guesses about how diagrams relating compressive strength to core diameter and core strength might look like, it is not clear what the relationship might be between diagrams of different shell strengths. Is there a predictable relationship between strength ratio and transition zone location? Would a predicted linear drop-off in the core failure zone be more rapid for a weaker shell concrete? Are there factors, such as large strength ratios, that would cause non-linear behaviour to develop? Given that it seems fairly clear that horizontal confinement is more dominant than vertical resistance, it may be that a lower strength shell will have less ability to confine the failing core, resulting in a general weakening of the member as a whole and implying a steeper linear drop-off in the core failure zone.

The stress-strain curves seemed to show a consistent behaviour. Core failure appeared to show a more marked drop-off at the end of the curve, possibly attributed to the sudden 'shock' due to core failure causing a sudden increase in either vertical stress or horizontal swelling or a combination of the two. It would be interesting to see if there are marked differences between curves close to but on either side of a transition zone, should such a zone be well-defined. However, due to the well-documented inconsistencies in gauge data, these results should, of course, be verified.

Conclusion

The analysis of the data in the present study appears to consistently support the failure model based on flexural theory put forward at the beginning. Although there were quite a few problems that consistently arose throughout the study, the comparative nature of the project rendered many of the problems to be largely irrelevant. In addition, it is interesting to note that although mistakes and oversights did occur, and some systematic errors were present, one mistake, namely the one that resulted in very weak core concrete being used in Test 3, was actually very beneficial to the study, as the results of Test 3 were able to give a fairly clear picture of how shell failure dynamics work, whereas if the strengths were kept consistently higher, the lack of importance of vertical resistance in the core may not have been so blatantly implied.

On the other hand, in order to better understand what is actually going on, especially if the present study should evolve into applications exploitable by industry, it will be necessary to be much more consistent in fabrication and testing methods, and to have better control over potentially confounding variables, such as workability and testability issues (in this case, the inconsistent results between the small and large cylinder tests). It is hoped that the results of the present study will provide an impetus to investigate hybrid cylinders further, if not for possible industrial applications (cost reduction, carbon sequestration, etc.), then at least for the manner in which it may be able to give a better understanding of the failure dynamics of concrete. Some outstanding questions that remain include:

- How predictable and reproducible could hybrid cylinders become with sufficient testing? For example, could governing equations relating shell/core strength/diameter ratios be generated that could give a good prediction of expected strength of a hybrid member? If so, would the applicability of hybrid columns (or something related such as FRP constrained columns) be sufficient to warrant attempting to pinpoint such a relationship?
- What is the optimum joint development? Is it better to allow an initial set? How would allowing a cold joint to form affect the performance? Would it act as a crack through the entire member and adversely weaken the structure by adding a potential failure surface? Can a multiplicative factor be found that will consistently predict the extent of strength loss due to the joint?
- Although it seems clear that there is a difference in behaviour between core and shell failure, how well defined is the transition zone? How does its location relate to absolute or relative core/shell strengths? Is there an optimal diameter where core and shell failure occur

simultaneously? Would this be desired?

- How much information can be gleaned from stress-strain curves? Are they really able to discern between shell and core failures? If so, how can the difference be summarized? Could stress-strain curves predict anomalies in the member? For example, if a core was deliberately located off-centre in the member, how would this affect the curve? And to what extent would it affect the overall strength?

References

[1] W.-F. Chen and T. Atsuta, "Stress-strain relations," in *Theory of Beam-Columns, Volume 1: In-Plane Behavior and Design*. Fort Lauderdale, FL: J. Ross Publishing, 2008, pp. 20-22.

[2] A. Van Der Neut, "The interaction of local buckling and column failure of thin-walled compression members," in *Applied Mechanics* (International Union of Theoretical and Applied Mechanics), eds. M. Hetényi and W. G. Vincenti. Heidelberg, Germany: Springer, 1969, pp. 389-399.

[3] A. Van Der Neut, "The sensitivity of thin-walled compression members to column axis imperfection," *Int. J. Solids and Structures,* vol. 9, no. 8, pp. 999-1011, Aug. 1973.

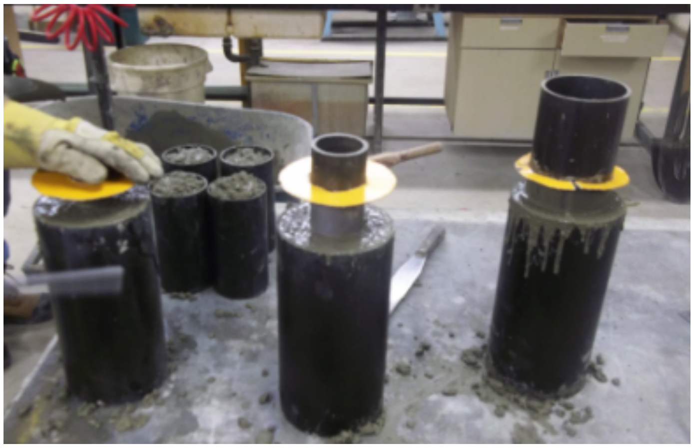
[4] J. M. T Thompson and G. M. Lewis, "On the optimum design of thin-walled compression members," *J. Mechanics and Phys. of Solids*, vol. 20, no. 2, pp. 101-109, May 1972.

[5] H. C. Fu, M. A. Erki, and M. Seckin, "Review of effects of loading rate on concrete in compression," *J. Struct. Eng.,* vol. 117, no. 12, pp. 3645-3659, Dec. 1991.

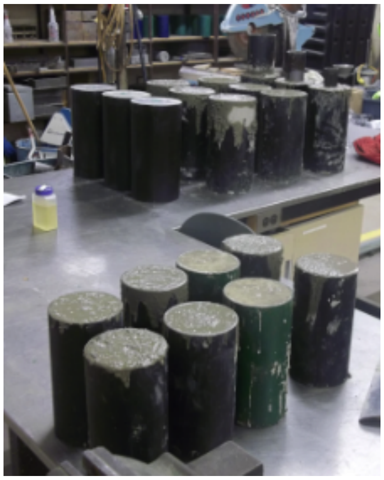
[6] R. L. Day, "Strength measurement of concrete using different cylinder sizes: a statistical analysis," *Cement, Concrete and Aggregates*, vol. 16, no. 1, pp. 21-30, Jun. 1994.

[7] P. M. Nielsen and L. C. Hoang, "Yield conditions," in *Limit Analysis and Concrete Plasticity*. Boca Raton, FL: Taylor and Francis Group, 2011, p. 47.

Appendix: Photos of Fabrication/Testing



Tapping on cylinders to help settling during Test 1 fabrication



Prepared Test 1 cylinders

Test 1 Fabrication Photos

Photos from Tests 1-4

Top view of hollow 2 7/8" cylinder

vo

1

rig

nder on
tachment

Test 4 'pink' reference cylinders waiting to be tested

: removal of n

Test 4 large cylinders before testing