

Under **THE COMMISSIONS OF INQUIRY ACT 1908**
In the matter of the **CANTERBURY EARTHQUAKES ROYAL COMMISSION
OF INQUIRY INTO THE COLLAPSE OF THE CTV
BUILDING**

STATEMENT OF EVIDENCE OF DOUGLAS JON HAAVIK

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BRIEF OF EVIDENCE OF DOUGLAS JON HAAVIK

1. My full name is Douglas Jon Haavik. I reside in Orange, California, USA. I am a consultant engineer specialising in concrete and concrete materials.
2. In accordance with the requirements of Rule 9.43 of the High Court Rules, I confirm that I have read the Code of Conduct for expert witnesses and that my evidence complies with the Code's requirements.
3. Matters on which I express an opinion are within my field of expertise.
4. I have no interests or relationships with any parties to these proceedings.

Qualifications and experience

5. I hold a Bachelor of Science (1966) and Master of Science (1968) in Civil Engineering from the University of California, Berkeley.
6. I am a Registered Civil Engineer, State of California (No. 21748). I am a member of the American Concrete Institute, Southern California Chapter, the American Society of Civil Engineers, Los Angeles, and the International Concrete Repair Institute, Los Angeles/Orange County Chapter.
7. After completing my studies in 1968 I was employed by a major US engineering/construction firm, as a materials engineer. My primary tasks were focussed on assessing and advising on damage to reinforced concrete structures, including repairs to structures involving the use of preplaced aggregate concrete, as well as epoxy injection and the injection of chemical and cementitious grouts for structural and/or waterproofing purposes. My duties also included training and qualifying technicians, as well as supervising other staff engineers specialising in concrete, welding and metals.
8. I entered private practice in 1986 and since then my primary work has been assessing damage to reinforced concrete structures from typical causes such as construction practices, fire, earth movement, reinforcing steel corrosion and others. My assessments generally provide a basis for repair recommendations and/or litigation support. Assignments (local and international) have ranged from initial to detailed field investigations through completion of the repair process, including writing specifications and qualifying and supervising a contractor to perform the work. Other assignments have involved providing project support to write specifications

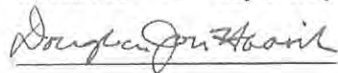
and to evaluate concrete materials and their capabilities: such services have been as extensive as supervising laboratory investigation work for several months, to holding discussions with potential suppliers followed by recommendations for specification changes. Litigation support has included engagements for both plaintiffs and defendants, primarily in construction defects and insurance claim cases.

9. I served as Chairman of the Subgroup on Materials, Construction and Examination of the Joint ACI-ASME Committee on Concrete Components for Nuclear Service (ACI 359) for over 10 years between 1978 and 1988.

Instructions and report

10. I have been instructed by Buddle Findlay, on behalf of Alan Reay Consultants Limited ("ARCL") to provide independent expert advice on concrete related issues relevant to the collapse of the CTV Building on 22 February 2011 following an earthquake of magnitude 6.3.
11. I have prepared a report outlining the results of the investigations I have conducted and commissioned and my opinion on the concrete strength of the CTV Building. My report is annexed and marked "A". Included with my report are the following appendices:
 - (a) Curricula Vitae for myself, Dr David Rothstein and Orville (Bud) Werner;
 - (b) Concrete Sampling Record Sheets prepared by ARCL;
 - (c) Petrographic Investigation report prepared by Dr David Rothstein of DRP Consulting, Inc.;
 - (d) Ultrasonic Pulse Velocity report prepared by Olsen Engineering, Inc.; and
 - (e) Concrete Core Test results report by Orville Werner of CTL | Thompson.
12. I confirm the contents of my report are true and correct.

Dated this 30th day of May 2012



D J Haavik

"A"

CANTERBURY TELEVISION BUILDING INVESTIGATION

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CANTERBURY TELEVISION BUILDING INVESTIGATION

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Executive Summary

The collapse of the Canterbury Television Building on 22 February 2011 resulted in the Department of Building and Housing commissioning Dr. Clark Hyland, and others, to investigate the collapse. Part of the investigation resulted in issuance of the “Hyland Materials Report” which included sampling and testing of concrete cores obtained from the building remnants. This report concluded that a likely factor in the building collapse was installed concrete below the specified strength at the time of original construction.

This conclusion and its supporting test results have been roundly criticized in a peer review issued by Dr. J. R. Mackechnie and a submission to the Royal Commission by the Cement & Concrete Association of New Zealand.

In an effort to better determine the concrete strength prior to the seismic events, a study of the concrete strength along with appropriate petrographic examination was commissioned by Buddle Findlay. This work consisted of testing eight cores removed from the column remnants of the building along with petrography.

This report details the criticisms of the “Hyland Materials Report” and gives results of the current test program, which showed compressive strengths with increases ranging from 2.7 % up to 55.8 % for the same columns in the “Hyland Materials Report”. It is likely that none of the current compressive strength test results was below the specified strength at the time of original placement.

Preface

An earthquake and series of aftershocks struck Christchurch, New Zealand, on 4 September 2010, 26 December 2010, and 22 February 2011. These events were of a serious magnitude and the 22 February 2011 event wreaked considerable devastation on the City of Christchurch. One of the results was a major collapse of the Canterbury Television Building (“CTV Building”), a reinforced concrete multiple-use building of six stories. The only substantial portion of the building left standing was the reinforced concrete elevator shafts and associated stairwells.

After the 22 February 2011 aftershock, the Department of Building and Housing commissioned Dr. Clark Hyland to investigate the failure. Dr. Hyland and his teams produced two reports [1] [2], referred to hereafter as the “Hyland Structural Report” and the “Hyland Materials Report”, and collectively as the “Hyland Reports”. Prior to the issuance of the Hyland Reports, Alan Reay Consultants, Ltd. (ARCL) had the opportunity to comment regarding any relevant information omitted from the reports and the relevant chapter of the Expert Panel Report. This was done by letter dated 22 December 2011, to Dr. David Hopkins of the Department of Building and Housing under the signature of Dr. Alan Reay on behalf of the firm [3]. ARCL is the designer of the building, and as such has an intimate knowledge and interest in the building’s performance.

Because there were few changes to the “Final” Hyland Reports issued after the comment period, ARCL embarked on a forensic investigation to determine if additional information could be obtained to better determine the causes of failure and assembled a team of structural engineers. Dr. Robin Shepherd, on behalf of the ARCL team, called the undersigned in mid-January 2012, after advising that a Civil Engineer specializing in Concrete and Concrete Materials would obtain useful information that was generally outside the Structural Engineering investigators primary expertise.

1. Scope of the forensic investigation

The Hyland Materials Report is an extensive document and includes concrete compressive strength test results obtained by testing concrete cores removed from various building elements as well as strengths determined using a Schmidt hammer. The data obtained from these studies indicated a probable cause to believe that some of the concrete was substantially below the appropriate strength. This data, however, is questionable for a variety of reasons put forth by several reviewers that will be considered later in this report.

In consideration of the above, Buddle Findlay, on behalf of Alan Reay Consultants, Ltd. authorized a program of forensic investigation of the concrete material, including the following elements: [1] obtain concrete cores from CTV Building remnants in New Zealand and have these core elements compression tested, including determination of ultrasonic pulse velocity and density, [2] perform petrographic examinations to determine the condition of the concrete, as appropriate, and [3] produce a report of the findings with appropriate discussion addressing the possible deficiencies in the Hyland investigation.

2. The investigators

In order to obtain forensic investigation expertise not currently associated with Christchurch earthquake investigations, it was necessary to go outside New Zealand;

investigators based in California and Colorado, United States of America, were engaged for the tasks.

The principal investigator (PI) and author of this report is Douglas J. Haavik, M.S., P.E., FACI (Fellow of the American Concrete Institute). Mr. Haavik graduated from the University of California, Berkeley, with a Master of Science in Civil Engineering (1968) and subsequently worked for the Bechtel organization for eighteen years, ultimately being the in-house concrete materials consultant for a large group of nuclear power plants. Since 1986, he has been an independent Consulting Engineer specializing in cement and concrete materials. He was part of a team that forensically investigated thirteen concrete structures after the 1994 Northridge Earthquake in California that was performed under the direction of Dr. Robin Shepherd.

The petrographic examinations shown as Appendix III to this report were performed by David Rothstein, Ph.D., P.G., FACI. Dr. Rothstein graduated from the University of California, Los Angeles, with a Ph.D. in Geology (1997) and subsequently was a Post-Doctoral Research Fellow at Northwestern University in Evanston, Illinois. He has been performing petrographic examinations since 1998 and has worked at his own firm, DRP Consulting, Inc., Boulder, Colorado, since 1999.

The compressive strength and density tests were performed under the direction of Orville R. "Bud" Werner II, B.Sc., P.E., FACI. Mr. Werner graduated from the Colorado State University, Fort Collins, Colorado, with a Bachelor of Science in Civil Engineering (1972). He is the Principal in the Denver, Colorado, office of CTL | Thompson, an independent testing laboratory. He has worked in the concrete supply industry since before graduation from college in various capacities for a variety of employers.

The above investigators have all read and agreed to comply with the Code of Conduct for Expert Witnesses, which we understand governs the standards of this investigation. More detailed *Curricula Vitae* are given in Appendix I.

3. Hyland Materials Report: reviews of concrete materials aspects

ARCL letter.— ARCL issued a comment letter on the draft Hyland Reports on 22 December 2011 [3]. Regarding concrete materials aspects, ARCL notes that analysis on the main columns suggests column concrete strengths to be as low as 11MPa (compared to a design strength of 35MPa). ARCL then comments "...it is considered unlikely that the in-situ strength would have been this low (or lower)". ARCL also mentions possible fire damage affecting compressive strengths, as well as possible microcracking and concludes that "...the test results must be viewed with caution".

ARCL notes that it is appropriate to consider the building according to the standards and practices at the time it was built, rather than evaluating it in accordance with the updated standards and practices today. ARCL also comments on the earthquake, noting “...the most likely actual cause of the collapse of the CTV Building: The CTV Building was subjected to an earthquake on 22 February 2011 of such powerful force that it was well in excess of the loads expected under the Code the building was designed under.”

Peer review.— Dr. J. R. Mackechnie produced a detailed and concise peer review of the concrete testing and interpretation given in the Hyland Materials Report for the Canterbury Earthquakes Royal Commission [4]. The undersigned recommends a thorough reading of Dr. Mackechnie’s peer review to anyone attempting to understand the concrete testing portions of the Hyland Materials Report. In lieu of such a reading, the following paragraphs note most of the salient items in Dr. Mackechnie’s review and, of necessity, duplicate some of his verbiage.

The review first criticizes concrete testing methodology, focusing on:

[1] Test element selection—could have found more useful cores with reduced damage to sample; sampling was done by drilling horizontally to the original orientation of the columns, limiting core diameters (possibly increasing variability in strength testing); horizontal cores more prone to near-surface damage from flexure and fire; suggested sawing columns and extracting cores from the center of the column in vertical orientation

[2] Core strength testing—no core logs are available documenting the condition, location and orientation of the samples before preparation; core strength test reports often failed to note mode of failure (or information was unclear); hardened density not reported in all cases; location and orientation of intersected reinforcement in core was often not given

[3] Schmidhammer testing—conducted on all columns (except C18, noticeably fire damaged); a “relatively tenuous correlation” was made between core strength test results and the hammer strengths and then inferred to 17 other columns; the reliability of these hammer strengths is influenced by the following unusual factors: a) surface deterioration due to fire exposure, b) surface preparation of concrete before testing, c) the calibration curve was developed over three different concrete mix designs where surface hardness would have varied due to different air entrainments and concrete proportions

[4] Microstructural assessment—assessment of concrete quality was done by visual means alone, although photos in the Hyland Materials Report suggest color changes due to fire in several cases; microscopic examination of off-cut core sections by a petrographer is suggested to establish the competence of the material before testing

Dr. Mackechnie also commented on the interpretation of concrete properties, generally as follows:

[1] core strength versus cylinder strength—Hyland does not address the issue of core strengths differing from cylinder strengths; core strengths are generally lower than cylinder strengths—possible reasons for this are core surface imperfections due to drilling as well as poorer curing and compaction of in-situ concrete as well as testing-related factors including aspect ratio, core diameter, presence of rebar, core moisture content and damage from drilling; additionally, rounded aggregates generally reduce strengths in concretes when compared to crushed aggregates

[2] Strength development with time—Hyland spoke of 25% long-term compressive strength development (based on Caltrans work), but Dr. Mackechnie notes that “It is often assumed that long-term core strengths would not expected to be significantly higher than the initial grade strength”.

[3] Target strength at construction—New Zealand concrete plants may be designated *Special Grade* based on “a proven testing regime where good technical control allowed the target to be set lower than for *High Grading* and thus had lower margins between design and target strength”; at the time of construction all Christchurch concrete plants were designated *Special Grade*, contrary to Hyland’s assumption that they were *High Grade* thus lowering the target strengths for the various concrete mix designs but not having any effect on the specified design strength

[4] Assessment of (core) damage—Visual examination to identify the presence of macro-cracking and any other obvious damage was the primary method of assessing pre-existing damage; “Petrographic examination of concrete would have provided valuable guidance” and “would have helped substantiate these findings and allowed more confident conclusions to be drawn”

Dr. Mackechnie notes the Hyland report makes no mention of the following information ordinarily produced at the time of the original construction. This information is a requirement for ready-mix concrete certified or audited by the New Zealand Readymix Concrete Association and, if available, would greatly improve the understanding of the concrete used in the structure:

- [1] Concrete mix designs (submitted by ready-mix suppliers to the contractor and design engineer)
- [2] Batch records for each truck load of concrete supplied to the project
- [3] Test certificates for concrete sampled at the concrete plant and on site
- [4] Any investigation reports about concrete issues during construction

Dr. Mackechnie notes that “(the above) data sources should have been investigated and any findings or omissions noted in the report” even if the passage of time has resulted in no detailed records being available.

Dr. Mackechnie provides an overall analysis of the findings, noting “Determining the strength of concrete at construction is not a simple matter of applying a strength correction factor of 25% and requires a more rigorous methodology. Comparison of estimated strength with target strength is further complicated by the Hyland report using High rather than Special grading.” He assumes strength test results for column C18 are unreliable due to high risk of fire and structural damage and notes that average core strengths of the other columns was 30.0 MPa, a value he finds consistent with “...grade 25 MPa concrete, which is the most likely strength grade for tested columns.” He cites “...column tR3, which had low density, core and hammer strengths. Unfortunately gaps in reporting adversely affect the reliability of this data since the concrete quality is uncertain...and the mode of failure was not reported.”

Dr. Mackechnie notes average test results for other structural elements was 29.0 MPa, including some strengths below 25 MPa “but these had moderate to high risk of cracking based on proximity of cores to macro-cracking observed in these elements. Density of cores was more consistent and within the general range expected for grade 25 MPa containing Christchurch greywacke aggregate. This would indicate that compaction and initial curing of concrete was adequate.”

Dr. Mackechnie provides “Analysis of core strengths...found the following relationships (albeit with fairly poor correlations):

- strength increased with an increase in core diameter

- strength increased with reduced risk of cracking (based on visual subjective rating...)
- embedded reinforcing steel did not have a consistent effect on core strength
- core strength increased with increasing hardened density of cores”

Dr. Mackechnie draws these conclusions (which have been selected for brevity):

“Concrete material testing outlined in the Hyland materials report is lacking in terms of sampling and testing detail.”

“The quality of information...makes general conclusions difficult to draw, most notably for columns designed to have strengths of 35 or 30 MPa (Level 1 and Level 2 columns respectively).”

“The report is unable to distinguish between the residual core strength after the collapse and the likely in-place strength before 22nd February 2011.”

“Average core strengths reported were not much higher than the minimum specified value of 25 MPa and were lower than would be expected after 25 years had it been a well cured and relatively intact structure. Concrete strengths reported from other structures investigated by the Royal Commission were found to have had higher core strengths that significantly exceeded design strengths (tests were however conducted on larger, intact elements). This discrepancy found in the strength of concrete from the CTV Building was attributed by the Hyland report to the inherently low strength of concrete rather than to significantly greater risk of micro-structural damage. This claim is not substantiated from the information given in the report and a more rigorous investigation would be required to provide convincing proof of this opinion.”

The Cement & Concrete Association of New Zealand has produced an extensive submission to the Canterbury Earthquakes Royal Commission [5] which states:

“The following conclusions on the Hyland Reports can be drawn from the CCANZ critique:

- “The Hyland Materials Report has not followed standard procedures in interpretation of concrete core strengths and Schmidt Hammer results.

- “The number of cores taken to draw firm conclusions on the concrete strength were inadequate, 19 cores were taken from only seven columns (7% of all CTV columns). As the specified design concrete strength reduced with the height of the building, and the floor level of five of the seven columns cored was unknown, this makes comparison of core strengths against specified strength problematic.
- “Core strengths have been compromised by being taken from areas of distressed concrete as a result of the building collapse and fire damage. These cores should have been rejected.
- “Aspect ratio (length/diameter) of three cores was less than 1.2, as against the recommended ratio of 1.9 – 2.1.
- “For five of the seven columns only two cores have been taken representing a particular column location. Sixteen of the nineteen cores were only 70 mm diameter, for which BS EN 13791 recommends six cores be taken for each column.
- “Three outlier results based on BS 6089 Pt 6.1 were not removed from the core results.
- “No allowance has been made for voidage in determining characteristic strength (or nominal strength) of standard specimens.
- “The correlation of the Schmidt Hammer testing against core strengths was based on only six pairs of strength vs. Hammer results. BS EN 13791 recommends a minimum of nine pairs. The correlation curve derived in the Hyland Materials Report is highly questionable, and has not taken variation in concrete strength between columns into account. This places all the concrete strength determination for nineteen columns based on Schmidt Hammer readings in doubt.
- “The Hyland assumption of compressive strength increase with time after 28 days is questionable in a New Zealand context. The Caltrans reference (USA) quoted is for external concrete containing a cement blend. This does not apply to cements used in New Zealand and should not apply to the CTV concrete.
- “CCANZ has the utmost confidence in the third party certified New Zealand Concrete Ready Mixed Association (NZRMCA)

Plant Audit Scheme, termed the Plant Classification Scheme in 1988. All concrete plants supplying the Christchurch metropolitan area at the time of the CTV construction were *Special Grade* plants under the scheme. The Scheme provides an independent audit of a ready mixed concrete plant's own quality system for compliance against NZS 3104:2003 *Concrete production* and the relevant parts of related documents."

The CCANZ Critique discusses the methodology of sampling, testing and reporting in the Hyland reports and the interpretation of concrete tests reports. These discussions raise concerns similar to the ones in Dr. Mackechnie's review.

The CCANZ Critique provides a discussion to show the problems with the Hyland Materials Report's evaluating concrete strengths assuming *High Grade* ready-mix plants. CCANZ presents evidence that all Christchurch ready-mix plants were *Special Grade* plants (Dr. Mackechnie agrees with this assertion in his review). This is important because "A *Special Grade* plant has a lower target mean strength of 3 MPa to reflect the higher level of quality control. Thus the data in Table 3 (page 63 in the Hyland Materials Report) are 3 MPa too high and the associated statistical data is in error. This also introduces an error into the distribution curves in Figures 51 and 52 (pp. 71 & 72) of the report." The Hyland Materials Report also uses an ageing factor of 25% on page 72. CCANZ states that it is inappropriate for the CTV concrete (Dr. Mackechnie holds a similar view).

The CCANZ Critique also provides an interpretation of the Hyland test results which gives details beyond the above conclusions.

4. Comments on the Hyland reports

Compressive strength test results.— The compressive strength test results presented in the Hyland Materials Report suggested the concrete was of substandard quality, particularly regarding compressive strength, and that condition was advanced as one of the reasons for the CTV Building's collapse. These compressive strengths also varied over a wide range, with some indicating a compressive strength below the lowest design requirement and some strengths substantially above the highest design requirement. CCANZ has reasonably proposed dismissing some of the lowest of strengths as outliers (11.0, 12.8 and 16.0 MPa) but since they are now part of the "Final Report" the PI deems it appropriate to consider them further.

The Hyland Reports imply that some proportion of the concrete was defective as delivered from the ready-mix plants used to supply the project and present their compressive strength testing to support this allegation. The lack of contemporaneous

batch plant and testing laboratory documentation for this project does not help refute the allegation. However, there are a few considerations that must be made: One is that the ready-mix plants were qualified to produce *Special Grade* concrete based on their operations under the Plant Audit Scheme per NZS 3104. This provides an independent and rigorous audit of the quality systems in place at a ready-mixed concrete plant on a continuing basis. The PI's opinion, while not familiar with the system details, is that such a scheme is likely to produce the desired concrete mix with the proper proportions as long as a gross error is not committed. The other consideration is that concrete resulting in strengths of 11.0, 12.8 and 16.0 MPa would be very difficult to make as delivered from a ready-mix plant. The concrete would likely have a very high slump and not be very cohesive. The labor force placing the concrete would likely complain that there is a problem with this material. Dr. Mackechnie also points out that the CTV building is the only building investigated by the Royal Commission that has low concrete strength advocated as a possible problem so it is reasonable to consider the question: why only one building? In the PI's opinion, the foregoing suggests, but doesn't confirm, that poor concrete from the ready-mix plant(s) was not the cause of these low strength test results.

The strength test results have to also be considered in the context of how the samples were obtained, treated and tested. At the risk of oversimplification, the PI understands that concrete cores were obtained from remnants of the structure including column stubs and the elevator and stairway core which were still standing at the original CTV Building site. Other remnants of the structure were sampled at the Burwood Landfill, including column segments stored in a separate area.

Core diameter issues.— The core diameters varied, with column samples about 69 mm and other structural elements varying from 57 mm up to 107 mm. It is well known that for a given concrete, core compressive strength test results increase with core diameter for the sizes of cores usually tested in structural investigations (up to about 152 mm diameter). The standard governing United States practice, ASTM C 42, Standard Method of Obtaining and Testing Drilled Cores and Sawed Beams of Concrete, specifies that, unless cores cannot be cut of these sizes, core diameters should be a minimum 3.70 in. (94 mm) and the diameter should be at least three times the maximum aggregate size dimension. For all the CTV Building concrete the maximum aggregate size was 19 mm which would imply a minimum core diameter of 57 mm, but this would be violating the 94 mm criteria. As all the column cores had diameters about 69 mm their test results must be viewed as tending to lower strengths when compared to strength test results derived from cores of a larger diameter. Correction factors have been proposed from many investigations, but ASTM and ACI do not endorse such an adjustment. The PI's opinion is that it is preferable to maximize the core diameter and accept the result as tested (subject to aspect ratio correction, discussed below). Additionally, selection of non-standardized correction factors will result in a varied interpretation of strength test results, with the possibility of the investigator not knowing what is actually being measured and giving results not comparable to other, perhaps relevant, investigations.

Aspect ratio.— Another important parameter is the aspect ratio, the ratio of core length (or height) to diameter. Ordinary cylinder tests on fresh concrete use molds that have an aspect ratio of 2.0 and core samples from structures usually attempt to maintain an aspect ratio as close to 2.0 as possible. Naturally, that is not always the case and ASTM C 39 specifies an adjustment to the test result to account for a reduction in aspect ratio. In United States practice, this is the only adjustment to actual test results endorsed or permitted by ASTM C 39, which is the only US Standard for this sampling and testing activity. ASTM C 39 indicates that a correction is made only if the aspect ratio is 1.75 or less. The PI has been informed that a “Factor D Adjustment” is the similar adjustment in New Zealand to account for varying l/d ratio.

Strength test adjustments.— The Hyland Materials Report proposed (and appeared to have used) adjustments [1] to account for strength reduction in cores due to compressive strength testing by loading perpendicular to the direction the concrete was placed and [2] to account for long-term strength gain between the time of construction and the time of collapse, a period of about 24 years (1987-2011). As previously noted, neither of these adjustments would be sanctioned in the US standard practices. The variation in strength due to orientation of loading is a real phenomenon, but the amount of variation could be dependent on a number of factors, primarily concrete mix design and materials. In the PI’s opinion, it is better to obtain cores that can be loaded parallel to the placement direction. The possible increase in compressive strength over time is more pronounced when using supplementary cementitious materials in the concrete (in addition to portland cement) and the CalTrans research cited in the Hyland Materials Report assumes the use of such materials, negating the applicability of this factor to the CTV concrete.

Schmidt hammer issues.— Extensive work with the Schmidt Hammer (ASTM C 805 - Standard Test Method for Rebound Number of Hardened Concrete) was a part of the Hyland Materials Report, in an apparent attempt to extend concrete strengths to elements that didn’t have cores removed. In the PI’s opinion, this effort was doomed to not work very well, as there were at least three different mix designs used for the differing strength requirements in the assortment of structural elements in Burwood Landfill. More mix designs may have been involved based on supply of concrete to the project from at least three different ready-mix plants. Even for situations involving only one concrete mix design ASTM C 805 states: “This test method is not intended as the basis for acceptance or rejection of concrete because of the inherent uncertainty in the estimated strength.” The PI would not recommend the use of the Schmidt Hammer to help determine strengths for this type of forensic investigation. That said, there may be instances where the Schmidt Hammer would be useful as a screening tool for various concrete elements.

Lack of petrographic examination.— Given the potential for microcracking and fire damage it is surprising that no petrographic work had been done as a part of Dr. Hyland’s studies. The large variability in compressive strength test results would highlight the need for a closer examination to better understand the range of strengths.

Cumulative damage issue.– The Hyland Materials Report [2, p. 50 & 56] contains statements to the effect that, after the authors’ review there was no evidence reported of significant change to the building’s seismic resisting capacity from both the 4 September 2010 and 26 December 2010 seismic events. The PI would like to report, for the record, his personal experience peripheral to his professional career expertise. The PI’s first employment was in the University of California, Berkeley Structures Laboratory, where, as an inexperienced high school student (prior to starting his college engineering education), he participated in fabricating and testing reinforced concrete frames under the watchful eyes of graduate students. The research was published [6] in the paper “Behavior of Reinforced Concrete Frames Subjected to Repeated Reversible Loadings.” These reinforced concrete frames were about 1150 mm wide and 1250 mm high, fabricated with #2 reinforcing bars and ties. They were restrained in a steel loading apparatus along the bottom of the frame and loads were applied through a system of weights and pulleys. Cyclic loads were applied and cracks appeared at the first loading, extending their length and width as more cycles and heavier loads were accumulated. Eventually the frames were taken to collapse and crushing of the concrete could be observed at the hinge locations.

This experience has instilled in the PI a strong sense that reinforced concrete subjected to strong loads will experience cumulative damage prior to collapse and that the CTV Building’s relatively rapid collapse in the 22 February 2011 event strongly suggests some inherent damage prior to that time.

5. Current forensic investigation

The current forensic investigation was undertaken because the results of the Hyland Materials Report concrete investigation was subject to the previously noted criticisms (Section 3 and Section 4) which in turn cast doubt about the usefulness of the test results. The PI’s opinion is that Dr. Hyland has determined concrete strengths influenced, to some unknown degree, by the collapse and fire. However, for structural analysis purposes information on the compressive strength prior to the collapse and fire is needed. Obtaining this information has been difficult because no records of mix designs, batch tickets and/or test results from the time of original construction have been found.

The PI started formulation of the current forensic investigation in February 2012 by proposing a program of limited coring and testing, along with petrographic examination. Dr. Rothstein and Mr. Werner subsequently joined the team and approval in New Zealand was granted to obtain cores from column elements stored at the Burwood Landfill. The program of obtaining cores was purposefully oriented to attempt to obtain concrete undamaged by the collapse and fire and to allow core testing loads to be applied parallel to the direction of the concrete placement. This was done by core drilling along the axis of column sections.

Core sampling by ARCL.— ARCL employees obtained the cores on 20 & 21 March 2012; Concrete Sampling Record Sheets documenting the sampling of the cores are assembled in Appendix II to this report. Generally, sections of a given column were cut along the height (as originally oriented in the structure) and then a core sample was removed by drilling in the center of the vertical axis of the column. This resulted in cores that had been confined within the vertical column steel and the spiral wrap or column ties, offering a measure of protection during the collapse and fire. These core diameters were approximately 145 mm, the lengths varied. Two shipments of cores were sent to Dr. David Rothstein's petrographic laboratory in Boulder, Colorado.

On 27 April 2012, the investigators met at Dr. Rothstein's laboratory and examined the cores. Dr. Rothstein documented the received condition in the Appendices of his petrographic examination report, which is included in this document as Appendix III. Three cores were received with partial fractures generally perpendicular to the core's axis (C1 T½, C4 B, C4 T½) extending part of the way around the core; one core (R7) was received in two pieces. The investigators formulated a plan to apportion the various core segments to the tests and examinations to be performed. The primary objective was to produce compressive strength test samples that would be of the maximum practicable diameter while producing a 2:1 aspect ratio. Of course, this was not achieved in all cases.

Initial core examination and selection for testing.— Generally, the core segments of full diameter and an appropriate length for compression testing were sent to CTL | Thompson where they were trimmed to provide a flat surface perpendicular to the core axis. After this preparation, the cores were tested by Olson Engineering, using an Ultrasonic Pulse Velocity (UPV) instrument to determine Pulse Velocity over both the length and diameter for each core tested. The results of these tests are given in Appendix IV of this report. All pulse velocity measurements "were above 12,000 ft/sec, which is the typical velocity for concrete considered to be of Sound condition." The pulse velocity studies were performed to give an added degree of confidence that the compression test specimens had no obvious latent defects prior to coring and compression testing.

A parallel effort was made in Dr. Rothstein's petrographic laboratory to cut and prepare samples for microscopic examination, including thin sections.

At the CTL | Thompson laboratory, weights of the cores were measured to allow density determinations based on weight and physical dimensions. The cores were then wrapped in plastic film and restrained using a plaster-like material in a 5 gallon pail so that they could be recored to maximize the number of specimens with an aspect ratio approximating 2:1.

After a drying time, the cores were tested in compression. The remaining annular segments from the recoring were used for density samples by the immersion method.

Concurrently, Dr. Rothstein performed microscopical petrographic examinations as well as point counts to determine material properties.

As previously noted, Dr. Rothstein's report of petrographic examination is attached as Appendix III and the CTL | Thompson's report is included as Appendix V.

6. Investigation results

Strength test results. – Compressive strength test results adjusted only for aspect (l/d) ratio (Appendix V, Table 2) indicate that all cores tested were above the 25 MPa specified strength requirement for columns at Level 3 and above. No cores contained any steel reinforcement. One core (R-3) tested in the 25 – 30 MPa strength range, two other cores (C-1-T, C-7-T) tested in the 30 – 35 MPa strength range. These results consistently showed Dr. Hyland's results were lower than the current concrete strength test results. Core R-3 is the only air entrained (4.6 %) core in the sample, which accounts for some reduced strength. The other five cores gave tested compressive strengths above 35 MPa. If one is willing to assume that R-3 does not represent a Level 1 or Level 2 column and that C-1-T and C-7-T do not represent Level 1 columns, then one can assume that all the cores in this study tested at an increase over the specified strength.

This is actually a good assumption, because only 2/3 of the columns need to meet a compressive strength requirement of 25 MPa. But it is still a statement that one cannot make with 100 % certainty.

The only samples in this study that can be related to a particular building location are Cores C-1-T and C-1-B, which are from Level 6. These two samples from the same column segment tested at corrected (l/d only) compressive strengths of 32.5 and 35.8 MPa, an average of 34.2 MPa. This is compared to a known specified strength requirement of 25 MPa. The Hyland Materials Report [2, page 93] showed an average core compressive strength of 23.3 MPa (individual core strengths of 26.5, 16.0, 27.5 MPa). It appears that Dr. Mackechnie [4, Table 1] rejected the 16.0 result and averaged the other two results to give 27.0 MPa. Whether the 16.0 result is used or not, the CTL data shows an 46.8 % increase over the Hyland data and a 26.7 % increase over Dr. Mackechnie's modification of Hyland's data..

In the CTL report the only other duplicate samples are Cores C-4-T and C-4-B, giving corrected strengths of 70.1 and 75.1 MPa, an average of 72.6 MPa. The Hyland Materials Report [2, page 93] showed an average core compressive strength of 46.6 MPa (individual core strengths of 47.8 and 45.3 MPa). This is a 55.8 % increase over the Hyland data. The actual data is probably a little bit higher, as ASTM C 39 indicates "For strengths higher than 6000 psi (42 MPa) correction factors may be larger than listed..." (Note 11)

For the remaining four cores, only one (R-3) is below the 30 MPa standard at 28.4 MPa. This core still tests substantially above the Hyland Materials Report cores [2, page 93], with average compressive strength test result of 20.3 MPa (individual core strengths of 20.5 and 20.1 MPa). This is a 39.9 % increase over the Hyland data.

The CTL report notes fracture types for the cores by numerically identifying the type according to the ASTM C 39 standard. Core C-4-B (the highest strength core) had a Type 1 fracture, identified by “Reasonably well-formed cones on both ends, less than 1 in. (25 mm) of cracking through caps.” All the other cores had a Type 2 fracture, identified by a “Well formed cone on one end, vertical cracks running through caps, no well defined cone on other end.” Type 3 is identified as “Columnar vertical cracking through both ends, no well formed cones.” For the majority of concrete strengths, the Type 1 and Type 2 cone fractures are indicative of suitable load application in the testing machine with appropriate friction between the machine and the bearing surface of the concrete. This friction results in a triaxial loading condition at the ends of the sample (loads in three dimensions) which helps form the cone structure and provides uniaxial loading in the middle portion of the sample. A Type 3 fracture usually suggests higher strength concretes.

Petrographic examinations. – Dr. Rothstein’s petrographic examinations were distinguished by the relative uniformity of the eight cores he examined. The cement and aggregates for all cores were similar, if not identical. The concrete samples represented were placed satisfactorily – good consolidation with minimal voids, no evidence of retempering (addition of water after the concrete left the ready-mix plant), only minor and occasional evidence of dirty aggregates. This is evidence of the constructors performing a proper job of handling and placing the concrete and is cause to have confidence in the continuity of the concrete as placed.

Dr. Rothstein saw minimal microcracking, for practical purposes almost none, so microcracking is not a significant factor in these test results. Dr. Rothstein also saw minimal relict and residual cement grains (RRCG), a parameter indicative of the degree of hydration of the concrete which relates to the availability of curing moisture. The highest-strength cores (C-4-T and C-4-B) had the largest RRCG range: 3 – 6 % and was rated as “normal hydration”. The next strongest core (R-7) had a RRCG range: 3 – 5 % and was rated as “normal to advanced hydration”. All other cores had < 3 % RRCG and were rated as “advanced hydration.” Clearly, these cores samples show well-hydrated, mature concretes, leaving little probability for further strength gain and reduction in strength due to microcracking. Of the microcracking observed, some of it had the presence of ettringite, a compound that forms in the presence of water. Dr. Rothstein observes the ettringite is compelling evidence that these microcracks formed prior to the current coring operations.

Dr. Rothstein observed no evidence of fire damage, visually on the as-received cores (Messrs. Haavik and Werner also observed this condition) and microscopically. In a practical matter, this confirms that the concrete inside the column ties and spirals was not damaged by fire.

Dr. Rothstein observed minimal secondary deposits, generally small rosettes of ettringite within minimal microcracking. Not observed were any deposits related to possible alkali-silica reaction nor was any carbonation observed.

Microscopical point count analysis (ASTM C 457) is usually used to study the presence of the amount of entrained and/or entrapped air, frequently to evaluate possible reasons for freeze-thaw damage. It also gives volumetric proportions of the paste (in this case cement and water) and aggregates (both fine and coarse).

Densities and absorption.– Table 1 – Test Results of Various Investigators Sampled from the Same Column – CTV Building shows CTL | Thompson density and absorption results. The absorption values are particularly interesting as they generally track the compressive strength test results: less absorption, more strength. The density values also tend to track the compressive strength test results, particularly for the high and low values of the strength tests: higher density, higher strength; lower density, lower strength.

6. Conclusions

This series of tests and examinations can best be viewed as a prototype for a full-scale test program to determine the condition of the CTV Building's concrete prior to the 22 September 2010 earthquake. The number of samples is not enough to draw definitive conclusions. One conclusion that can be drawn rather easily is that samples in this test program from the same column remnants as the Hyland Materials Report in each case produced higher concrete core compressive strength test results than their Hyland counterparts. The measured strength (corrected for l/d) increase ranged from a low of 2.7 % for Core C-7-T to a high of 55.8 % for the average strength of Cores C-4-T and C-4-B. All the strength increases are given in Table 1 and range somewhat uniformly between the high and low values.

The PI's opinion on the reasons for these differences in concrete strengths is that:

[1] CTL-tested cores were about 99 mm in diameter, while the Hyland cores were about 69 mm in diameter. This gives a substantially larger test area and reduces the "edge effect", the result of coring samples and disturbing and possibly loosening the aggregates. It is well-known that increases in diameter of cored samples result in an increase in tested strength.

[2] CTL-tested cores received test loads in the direction they were cast, while the Hyland cores were loaded perpendicular to the cast direction. According to the Hyland Materials Report [2, p. 61] these sample mean strengths have been already increased by 8 %, in accordance with Concrete Society recommendations. There is no assurance that 8 % is an accurate or appropriate factor, particularly given the tendency of these coarse aggregates to tend to a flat shape.

[3] The Hyland Materials Report gives no information that would assure their test results are not affected by microcracking or fire damage. This report gives assurance that the data is not affected by these factors.

In evaluating and comparing the strength test results from these two groups of tests the above factors should be kept in mind with the knowledge that these two groups of samples are from the same concrete members but they are very different as to how they were obtained and tested. They would certainly not necessarily be expected to give the same results.

The concrete strengths shown in Appendix V and reproduced in Table 1 provide enough test results so that the PI holds the opinion that further testing, coupled with Dr. Rothstein microscopically evaluating the cement paste to group the cores into 25 and 35 MPa groups would provide greater assurance that nearly all cores represent an appropriate strength level, testing above the specified strength.

The PI holds the opinion that the results of these tests and examinations have shown there is no reason to believe that there was a systematic reduction in concrete strength supplied to the project and that any such strength reduction is likely attributable only to gross error for a specific load of concrete which itself is extremely unlikely.

The PI strongly believes that this report should be taken as a “work-in-progress”, subject to further information being developed using the methods outlined herein. The PI invites questions if there is any misunderstanding of this report and encourages those investigators to bring forth information they deem useful so that the report can be appropriately updated.



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California Registered Civil Engineer, C-21748, Exp. 9/30/2013



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- [6] Bertero, V. V., and McClure, George, “Behavior of Reinforced Concrete Frames Subjected to Repeated Reversible Loadings”, Journal of the American Concrete Institute, Title No. 61-66.

Table 1 – Test Results of Various Investigators Sampled from the Same Column – CTV Building

CTL Core Identification	CTL Thompson Test Results					Hyland Materials Report Test Results			Other Parameters			
	As-Received Density (Dimensional) kg/m3	Compression Test Density (Dimensional) kg/m3	Aspect (l/d) Ratio	Corrected Compressive Strength MPa	Annular Density (Soaking) kg/m3	Annular Density (Dry) kg/m3	Absorption By Soaking %	Column Identification	Core Strength Test Results MPa	Hyland Average Compressive Strength MPa	Mackechnie Average Compressive Strength MPa	Compressive Strength Increase CTL Hyland %
C-1-T	2341	2336	1.63	32.5	2374	2267	4.7	IC1	26.5, 16.0, 27.5	23.3	27.0	46.6
C-1-B	2358	2358	2.00	35.8	2397	2280	5.1					
C-4-T	2435	2397	1.51	70.1	2436	2365	3.0	IC4	47.8, 45.3	46.6	46.6	55.8
C-4-B	2431	2416	1.13	75.1	2429	2358	3.0					
C-7-T	2390	2374	1.14	30.3	2414	2307	4.6	IC7	29.5	29.5	NR	2.7
C-12-B	2368	2357	1.09	39.1	2395	2298	4.2	IC12	27.1, 26.2	26.7	26.7	46.4
R-3	2307	2292	1.96	28.4	2338	2225	5.0	IR3	20.5, 20.1	20.3	39.9	39.9
R-7	2374	2356	1.98	48.2	2387	2303	3.6	IR7	39.5, 42.2	40.9	40.9	17.8

Note: CTL | Thompson compressive strengths are individual core results.

APPENDIX I

CURRICULA VITAE

OF THE INVESTIGATORS

DOUGLAS J. HAAVIK

CONSULTING ENGINEER

Concrete and Concrete Materials

Mr. Haavik entered private practice in 1986 after 19 years as materials engineer for a major engineering/construction firm. Previously, he obtained extensive laboratory experience while a student at the University of California.

CAREER HISTORY

In private practice, Mr. Haavik's primary work has been assessing damage to reinforced concrete structures from typical causes: construction practices, fire, earth movement, reinforcing steel corrosion and others. These assessments provide a basis for repair recommendations and litigation support. Assignments (local and international) have ranged from initial to detailed field investigations through completion of the repair process, including writing specifications and qualifying and supervising a contractor to perform the work. Other assignments have involved providing project support to write specifications and to evaluate concrete materials and their capabilities: such services have been as extensive as supervising laboratory investigation work for several months, to holding discussions with potential suppliers followed by recommendations for specification changes. Litigation support has included service for both plaintiffs and defendants, primarily in construction defects and insurance claim cases.

Previously, Mr. Haavik performed comparable assignments while employed by a major engineer/constructor which also included repairs to structures involving the use of preplaced aggregate concrete, as well as epoxy injection and the injection of chemical and cementitious grouts for structural and/or waterproofing purposes. His previous duties also included training and qualifying technicians, as well as supervising other staff engineers specializing in concrete, welding and metals.

EDUCATION AND PROFESSIONAL DATA

Bachelor of Science (66), Master of Science (68)--Civil Engineering, University of California, Berkeley.

Registered Civil Engineer, State of California No. C 21748.

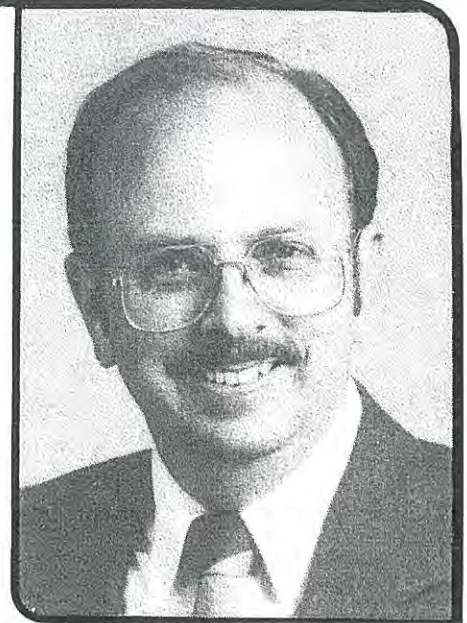
Member: American Concrete Institute, Southern California Chapter
American Society of Civil Engineers, Los Angeles
International Concrete Repair Institute, Los Angeles/Orange County Chapter

Mr. Haavik served as Chairman of the Subgroup on Materials, Construction and Examination of the Joint ACI-ASME Committee on Concrete Components for Nuclear Service (ACI 359), and as a member of ACI's Cold Weather Concreting committee (ACI 306) for over 10 years.

Professional references, expanded assignment/employment descriptions, and a list of publications are available upon request.

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Civil Engineer, Specialist in Concrete, Concrete Materials, and Related Testing and Investigations

Personal: Born May 6, 1950, Monte Vista, Colorado

Education: B. Sc. in Civil Engineering, Colorado State University, Fort Collins, CO 1968 – 1972, Graduated with Honors

Professional:

Registration: Registered Professional Engineer, Colorado
P.E. # 14540, 1976; Idaho P.E. #11882, 2005

Associations: Fellow, American Concrete Institute
Member about 30 years
Past President of Rocky Mountain Chapter
Participated in numerous committees
International Concrete Repair Institute
American Society for Testing and Materials
Member about 30 years
Participated in C-1 (Cement) and C-9
(Concrete and Concrete Aggregates)
NRMCA Approved Plant Inspector #803724 (2008)

Areas of Expertise:

Concrete failure investigations.
Concrete durability.
Analysis of fresh and hardened concrete, using
routine and specialized testing techniques.
Specifying concrete repair methods and
materials.
Selecting materials for concrete production.
Conducting trial mix studies.
Testing cement and fly ash.
Placement, and curing of concrete.

Employment History:

July 1983 to present
CTL|Thompson Materials Engineers, Inc.
(See company link at www.ctlt.com)
Current title: President and Principal Engineer.

March 1974 to July 1983

**Bureau of Reclamation, Engineering and
Research Center, Concrete and Structural
Branch**

**Title at Departure: Supervisory Civil Engineer,
Concrete Section**

June 1972 to March 1974

**Bureau of Reclamation, Fryingpan-Arkansas
Project, Twin Lakes Construction Office**

Title: Civil Engineer, Construction Inspector

Summers, 1968, 1969, 1970

**Responsible for quality control at concrete
aggregate production plants in Colorado and
Oklahoma. (Fountain Sand and Gravel)**

Experience:

Summary: Mr. Werner is a recognized expert in the field of concrete technology. His experience has included 40 years of work in the construction industry. He has had significant duties in concrete materials research, concrete specifications writing, conducting training in concrete construction technology for field inspectors, testing fresh and hardened concrete for a wide variety of properties, concrete construction project inspection, analysis of failed concrete, repair of concrete, and expert witness.

Mr. Werner has worked in the public and private sectors, he has worked on small and large projects, and he has actively participated in the process of publishing standards for the industry through ACI and ASTM.

Representative Projects:

Laboratory testing-

**Developed first independent laboratory capabilities
for testing in Rocky Mountain Region for :**

- **Modern ASR testing of aggregates**
- **Creep testing of concrete**
- **Sulfate durability testing of cementitious
matl's.**
- **Quality conformance testing of fly ash /
cement**
- **Tensile testing of concrete**

Evaluation, Consultation, and Repair Projects

Apple Computer Floor Repair, Fountain CO

Aldi Floor Topping Repair, Webberville, MI
Coyote Power Plant Cooling Tower, MT
Dillon Reservoir Glory-Hole Spillway Rehabilitation,
Dillon, CO
Shadow Mountain Dam Spillway Rehabilitation,
Granby, CO
Lennox Floor Repair, Denver, CO
First Bank Parking Garage Resurfacing, DTC,
Denver, CO
I-70 Panel Replacement, Wadsworth to I-25, Denver,
CO
Hinze Dam Trial Mix Studies, Queensland, Australia
Concrete mix design consultation, Solaris Project,
Vail, Colorado (Mass concrete and high-
volume flowable grout.)

Full-Time Construction Project Participation
Fryingpan-Arkansas (USBR), Twin Lakes
Powerplant Construction, Construction
Inspector
Fryingpan-Arkansas (USBR), Nast Tunnel
Construction and Lining (concrete and
shotcrete), Construction Inspector

Representative Litigation (work for defendants and
plaintiffs)

Denver International Airport – (Various concrete
pavement issues.)
Denver area – Multiple disputes over deteriorating
concrete flatwork in residential projects.
C-470, Lakewood, CO – Dispute over concrete
pavement conformance with CDOT
specifications.
(More detailed list available on request.)


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David Rothstein, Ph.D., P.G., FACI

EDUCATION

1992-1997	Ph.D., Geology	University of California-Los Angeles
1988-1990	M.S., Geology	Northern Arizona University (Flagstaff)
1982-1986	Certificate in Environmental Studies	University of Wisconsin-Madison
1981-1985	B.S., Geology	University of Wisconsin-Madison

REGISTRATION

Professional Geologist	State of California No. 7168
Professional Geologist	State of Illinois No. 196-001060

WORK EXPERIENCE

President, DRP Consulting, Inc. (Boulder, Colorado), 1999-present

1999-present

- * Principal of firm providing petrographic analysis and consultation for characterization of earth materials and performance of cement-based construction materials, aggregates and natural rock products.

Post-Doctoral Research Fellow, Department of Civil Engineering, Northwestern University (Evanston, Illinois); 1999-2001

- * Research on durability, chemistry and microstructure of cement-based materials.

Consultant in Concrete Technology (Santa Monica, California), 1998-1999

- * Consultant providing petrographic analysis of concrete and construction aggregate performance.

Instructor, Department of Geology, California State University-Dominguez Hills, 1998-1999

- * Instructor for Introductory Geology course.

Project Manager, Carlisle & Anderson, Inc. (Santa Monica, California), 1997-1998

- * Geologic exploration and evaluation of mineral and construction aggregate resources, southeastern California.

Exploration Geologist, Touchstone Resources, World Wide Minerals, Inc., Ontario Ltd., Inc., 1990-1997

- * Geologic, geochemical and geophysical exploration of epithermal gold-silver districts throughout Nevada.

PROFESSIONAL SOCIETIES

American Concrete Institute Member since 2000. Fellow of the Institute. Voting member on Committees on Durability (201), Aggregates (221); Materials Science of Concrete (236); and Plastering (524). Past President of Rocky Mountain Chapter (2005). Co-Chair Fall 2006 Denver National Convention.

American Society of Testing and Materials Member since 1999. Committee C-09 on Concrete and Concrete Aggregates; voting member on sub-committees C 09.20 (Aggregates); C 09.26 (Chemical Reactions); C9.50 (Risk Management for Alkali-Aggregate Reactions); C 09.65 (Petrography), and C 09.69 (Miscellaneous Tests).

Society of Concrete Petrographers Member since 2004.

International Concrete Repair Institute Member since 2002.

Mineralogical Society of America Member since 1992.

Geological Society of America Member since 1988.



SELECTED PUBLICATIONS & PRESENTATIONS

- Rothstein, D., Carrasquillo, R. L., and Garza, C., 2012, Field and laboratory assessment of cracking damage from alkali-aggregate reactions in concrete slabs on ground, column footings and perimeter foundations, Midwest USA, *Proceedings, 14th International Conference on Alkali-Aggregate Reactions (ICAAAR)*, Austin, Texas.
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- Rothstein, D., 2008, Value of Petrography as a Tool for Evaluating the Quality of Concrete in a Structure, *invited paper presented at the Seminario de la Beca for the Congreso Puertorriqueño del Hormigón*, San Juan, Puerto Rico.
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APPENDIX II

CONCRETE SAMPLING RECORD SHEETS

ALAN REAY CONSULTANTS

20 & 21 MARCH 2012

Concrete Sampling Record Sheet



Column identifier:	C1
Date of sampling:	20/03/2012
Sampled by:	DL/CU
Weather:	Fine
Location in building:	400 diameter column, Level 6, plan location unknown
Design concrete strength:	25 Mpa
Nominal aggregate size:	19mm

Photo of column:



Sampling Procedure:

Samples have been obtained in accordance with ASTM C42/C42M

The general procedure was:

- Photographs were taken of the column
- Schmidt rebound hammer readings were taken
- A concrete saw was used to obtain approximately 330mm long segments of column
- The segments were rotated so that the cut surfaces were horizontal
- A core drill was used to obtain approximately 150mm cylindrical core specimens
- Cores were taken at the centre of the column, in the vertical orientation
- A concrete saw was used to square off the top and bottom of the cores
- Samples were wiped and dried, then bagged and sealed within 1 hour

Sample identifier:	C1-T	C1-B
Begin coring:	12:34pm	12:59pm
Finish coring:	12:47pm	1:29pm
Ends cut:	Not cut	Not cut
Diameter of core:	145mm approx	145mm approx
Length of core:	130+210mm approx	120+220mm approx
Bagged and sealed:	1:35pm	2:18pm
Notes:	Sample broken due to pre-existing crack in concrete	Sample broken due to pre-existing crack in concrete

Photos of samples:

C1-T



C1-B



Signed:

Alottan

Concrete Sampling Record Sheet



Column identifier: C4
Date of sampling: 20/03/2012
Sampled by: DL/CU
Weather: Fine
Location in building: 400 diameter column, location unknown
Design concrete strength: 25-35 Mpa
Nominal aggregate size: 19mm

Photo of column:



Sampling Procedure:

Samples have been obtained in accordance with ASTM C42/C42M

The general procedure was:

- Photographs were taken of the column
- Schmidt rebound hammer readings were taken
- A concrete saw was used to obtain approximately 330mm long segments of column
- The segments were rotated so that the cut surfaces were horizontal
- A core drill was used to obtain approximately 150mm cylindrical core specimens
- Cores were taken at the centre of the column, in the vertical orientation
- A concrete saw was used to square off the top and bottom of the cores
- Samples were wiped and dried, then bagged and sealed within 1 hour

Sample identifier:	C4-T	C4-B
Begin coring:	2:11pm	1:36pm
Finish coring:	2:49pm	2:04pm
Ends cut:	Not cut	Not cut
Diameter of core:	145mm approx	145mm approx
Length of core:	200+140mm approx	230mm approx
Bagged and sealed:	3:45pm	2:45pm
Notes:	Sample broken due to pre-existing crack in concrete	Sample broken due to pre-existing crack in concrete

Photos of samples:

C4-T



C4-B



Signed:

D. L. Hansen

Concrete Sampling Record Sheet



Column identifier: C7
Date of sampling: 20/03/2012
Sampled by: DL/CU
Weather: Fine
Location in building: 400 diameter column, location unknown
Design concrete strength: 25-35 Mpa
Nominal aggregate size: 19mm

Photo of column:



Sampling Procedure:

Samples have been obtained in accordance with ASTM C42/C42M

The general procedure was:

- Photographs were taken of the column
- Schmidt rebound hammer readings were taken
- A concrete saw was used to obtain approximately 330mm long segments of column
- The segments were rotated so that the cut surfaces were horizontal
- A core drill was used to obtain approximately 150mm cylindrical core specimens
- Cores were taken at the centre of the column, in the vertical orientation
- A concrete saw was used to square off the top and bottom of the cores
- Samples were wiped and dried, then bagged and sealed within 1 hour

Sample identifier:	C7-B	C7-T
Begin coring:	11:16am	10:52am
Finish coring:	11:27am	11:05am
Ends cut:	11:32am	11:15am
Diameter of core:	145mm approx	145mm approx
Length of core:	290mm approx	295mm approx
Bagged and sealed:	12:17pm	11:54am
Notes:		

Photos of samples:

C7-B



C7-T



Signed:

[Handwritten signature]

Concrete Sampling Record Sheet



Column identifier:	C12
Date of sampling:	21/03/2012
Sampled by:	DL
Weather:	Fine
Location in building:	400 diameter column, location unknown
Design concrete strength:	25-35 Mpa
Nominal aggregate size:	19mm

Photo of column:



Sampling Procedure:

Samples have been obtained in accordance with ASTM C42/C42M

The general procedure was:

- Photographs were taken of the column
- Schmidt rebound hammer readings were taken
- A concrete saw was used to obtain approximately 330mm long segments of column
- The segments were rotated so that the cut surfaces were horizontal
- A core drill was used to obtain approximately 150mm cylindrical core specimens
- Cores were taken at the centre of the column, in the vertical orientation
- A concrete saw was used to square off the top and bottom of the cores
- Samples were wiped and dried, then bagged and sealed within 1 hour

Sample identifier:	C12
Begin coring:	9:22am
Finish coring:	9:38am
Ends cut:	Not cut
Diameter of core:	145mm approx
Length of core:	160+120+40mm approx
Bagged and sealed:	10:23am
Notes:	Sample broken due to pre-existing crack in concrete

Photos of samples:

C12



Signed:

[Handwritten signature]

Concrete Sampling Record Sheet



Column identifier:	R3
Date of sampling:	21/03/2012
Sampled by:	DL
Weather:	Fine
Location in building:	400x300 column, Grid A, level unknown
Design concrete strength:	25-35 Mpa
Nominal aggregate size:	19mm

Photo of column:



Sampling Procedure:

Samples have been obtained in accordance with ASTM C42/C42M

The general procedure was:

- Photographs were taken of the column
- Schmidt rebound hammer readings were taken
- A concrete saw was used to obtain approximately 330mm long segments of column
- The segments were rotated so that the cut surfaces were horizontal
- A core drill was used to obtain approximately 150mm cylindrical core specimens
- Cores were taken at the centre of the column, in the vertical orientation
- A concrete saw was used to square off the top and bottom of the cores
- Samples were wiped and dried, then bagged and sealed within 1 hour

Sample identifier:	R3
Begin coring:	10:59am
Finish coring:	11:18am
Ends cut:	Not cut
Diameter of core:	145mm approx
Length of core:	80+260mm approx
Bagged and sealed:	12:01pm
Notes:	Sample broken due to pre-existing crack in concrete

Photos of samples:

R3



Signed:

Alakran

Concrete Sampling Record Sheet



Column identifier:	R7
Date of sampling:	21/03/2012
Sampled by:	DL
Weather:	Fine
Location in building:	400x300 column, Grid A, level unknown
Design concrete strength:	25-35 Mpa
Nominal aggregate size:	19mm

Photo of column:



Sampling Procedure:

Samples have been obtained in accordance with ASTM C42/C42M

The general procedure was:

- Photographs were taken of the column
- Schmidt rebound hammer readings were taken
- A concrete saw was used to obtain approximately 330mm long segments of column
- The segments were rotated so that the cut surfaces were horizontal
- A core drill was used to obtain approximately 150mm cylindrical core specimens
- Cores were taken at the centre of the column, in the vertical orientation
- A concrete saw was used to square off the top and bottom of the cores
- Samples were wiped and dried, then bagged and sealed within 1 hour

Sample identifier:	R7
Begin coring:	10:22am
Finish coring:	10:48am
Ends cut:	Not cut
Diameter of core:	145mm approx
Length of core:	260+70mm approx
Bagged and sealed:	11:32am
Notes:	Sample broken due to pre-existing crack in concrete

Photos of samples:

R7



Signed:

Platman

APPENDIX III

PETROGRAPHIC EXAMINATION OF

CONCRETE COLUMN CORES

RECOVERED FROM THE

CTV BUILDING COLLAPSE

DRP CONSULTING, INC.

24 MAY 2012

Petrographic Investigation of Concrete Column Cores
Recovered from the CTV Building Collapse
Located in Christchurch, New Zealand



Prepared for: Mr. Willie Palmer
Buddle-Findlay
Christchurch, New Zealand

Prepared by: David Rothstein, Ph.D., P.G., FACI
Report No.: DRP12.960

24 MAY 2012

EXECUTIVE SUMMARY

Eight (8) concrete cores extracted from columns recovered from the collapsed CTV Building in Christchurch, New Zealand are subjects of petrographic examination and microscopical air content determination to evaluate the general composition and condition of the concrete represented by the cores. The findings from this scope of work indicate that the constituents used to produce the concrete represented by the samples are broadly consistent. The paste fraction of the concrete represented by the cores consist of hydrated portland cement with no fly ash, slag cement or other supplemental cementitious materials observed. The aggregates are siliceous in composition and have a nominal top size of 19 mm. None of the cores are air-entrained except Core R3, which contains 4.6% air.

The hydration of the cement is normal. Optical and physical properties of the paste indicate that the concrete represented by the cores was proportioned with a range of water-cement ratios that are broadly consistent with the 25-35 MPa 28-day design strengths indicated for the columns.

The rocks that make up the aggregates are hard and competent and consist primarily of metagraywackes with minor granitic rocks. The particles are well rounded to sub-round and a few cores showed evidence of sandy coatings in aggregate sockets. These factors may account for the passage of both as-received and fresh fractures predominantly around aggregate particles.

The cores are well consolidated with no large entrapped voids or bleed voids observed.

No evidence of fire damage was observed.

The cores do not show evidence of extensive microcracking but a few cores contain occasional microcracks that contain deposits of ettringite. Ettringite is also commonly observed in air voids. Ettringite is significant because it forms in portland cement concrete that is exposed to moisture for a prolonged period of time. Consequently, the presence of ettringite in microcracks is compelling evidence that the microcracks were present before the recent coring of the columns that provided the samples for the present investigation.

1.0 INTRODUCTION

Mr. Willie Palmer of Buddle-Findlay (**BF**) located in Christchurch, New Zealand requested **DRP** Consulting, Inc. (**DRP**) to investigate the general condition and composition of concrete represented by cores extracted from reinforced concrete columns recovered from the collapsed CTV Building located in Christchurch, New Zealand. On 4 April 2012 **DRP** received five (5) concrete cores from **BF** and an additional six (6) cores were received from **BF** on 26 April 2012. **DRP** also received documents prepared by Alan Reay Consultants (**ARC**) titled "Concrete Sampling Records". These documents contained information relevant to the extraction of the cores from the recovered columns that were in turn submitted to **DRP** for testing. Each core was reportedly extracted from the central portion of the columns and each core measured 145 mm in diameter. **Table 1** summarizes information regarding the received cores and their testing schedule for the present investigation.

Table 1. Summary of Core Information and Testing Schedule

ARC No.	DRP No.	Location	Length	Design Strength	Testing Schedule
<i>Samples Received 4 April 2012</i>					
C1 B	16YD5330	400 mm diameter column 6 th Level	250 mm	25 MPa	Physical Properties (CTL T) UPV (OE)
C1 B ½	16YD5331	400 mm diameter column 6 th Level	120-140 mm	25 MPa	Petrography (DRP)
C1 T ½	16YD5332	400 mm diameter column 6 th Level	95-145 mm	25 MPa	Petrography ^a (DRP)
C4 B	16YD5333	400 mm diameter column Unknown Location	210-275 mm	25-35 MPa	Physical Properties (CTL T) UPV (OE) Petrography ^a (DRP)
C4 T ½	16YD5334	400 mm diameter column Unknown Location	200-215 mm	25-35 MPa	Physical Properties (CTL T) UPV (OE)
<i>Samples Received 26 April 2012</i>					
C1 T ½	16YD5358	400 mm diameter column 6 th Level	245 mm	25 MPa	Physical Properties (CTL T) UPV (OE)
C4 T ½	16YD5359	400 mm diameter column Unknown Location	125 mm	25-35 MPa	Petrography (DRP)
C7 T ½	16YD5360	400 mm diameter column Unknown Location	300 mm	25-35 MPa	Physical Properties (CTL T) UPV (OE) Petrography ^a (DRP)
C12 B ½	16YD5361	400 mm diameter column Unknown Location	110-155 mm	25-35 MPa	Physical Properties (CTL T) UPV (OE) Petrography ^a (DRP)
R3	16YD5362	400 x 300 mm column Grid A, Level Unknown	240-260 mm	25-35 MPa	Physical Properties (CTL T) UPV (OE) Petrography ^a (DRP)
R7	16YD5363	400 x 300 mm column Grid A, Level Unknown	330 mm	25-35 MPa	Physical Properties (CTL T) UPV (OE) Petrography ^a (DRP)

* Abbreviations are as follows: CTL|T indicates CTL|Thompson, OE indicates Olson Engineering and UPV = ultrasonic pulse velocity. Physical properties includes compressive strength, density and absorption. Petrography indicates petrographic examination following ASTM C856. Petrography^a indicates microscopical air content determination following ASTM C457 in addition to petrographic examination.

2.0 SCOPE OF WORK

The scope of work performed by **DRP** involved petrographic analysis of the cores according to ASTM C856 [1] and microscopical determination of the hardened air content of the concrete according to ASTM C457 [2]. This report summarizes the findings of this scope of work. *Appendices A-H* contain the notes, photographs and photomicrographs from the petrographic examinations and *Appendix I* contains the results of the microscopical air content determinations. *Appendix J* describes the procedures used to perform this scope of work.

The petrographic work performed by **DRP** was done to provide the following:

- (1) A methodical assessment of the microstructural properties and general condition of the materials represented by the cores;
- (2) An evaluation of the consistency of the concrete-making materials and methods used to produce the concrete represented by the cores; and
- (3) An evaluation of microstructural factors that could influence the results obtained by testing the concrete for physical properties such as compressive strength. In particular, the examinations focused on the extent of microcracking in the concrete and determining whether any of the concrete represented by the cores suffered from fire damage.

DRP also facilitated the transmittal of core samples to CTL|Thompson Materials Engineers, Inc. (CTL|T) in Denver, Colorado for testing the compressive strength, density and absorption of the cores. Ultrasonic pulse velocity measurements of the cores were done by Olson Engineering, Inc. (OE), located in Wheat Ridge, Colorado, while the cores were at the CTL|T facility. The methods used to perform these tests and the data obtained from these tests are discussed elsewhere.

1 *Standard Practice for Petrographic Examination of Hardened Concrete*. Annual Book of ASTM Standards, Vol. 4.02., ASTM C856-04.

2 *Standard Test Method for Microscopical Determination of Parameters of the Air-Void System in Hardened Concrete*, Annual Book of ASTM Standards, Vol. 4.02, ASTM C457-06.

3.0 FINDINGS

The following findings are relevant to the concrete represented by the cores.

- 3.1 Orientation/Dimensions/As-Received Condition** All the cores are vertical in orientation and measure 145 mm in diameter. The length of the cores ranges from 95-330 mm. The ends of most of the cores are fracture surfaces or mixed saw-cut and fracture surfaces; Core C7 T has saw cuts at both ends (**Figure 1**). All of the cores were hard and compact and gave a light ring when sounded with a hammer. None of the cores contained embedded steel reinforcement.

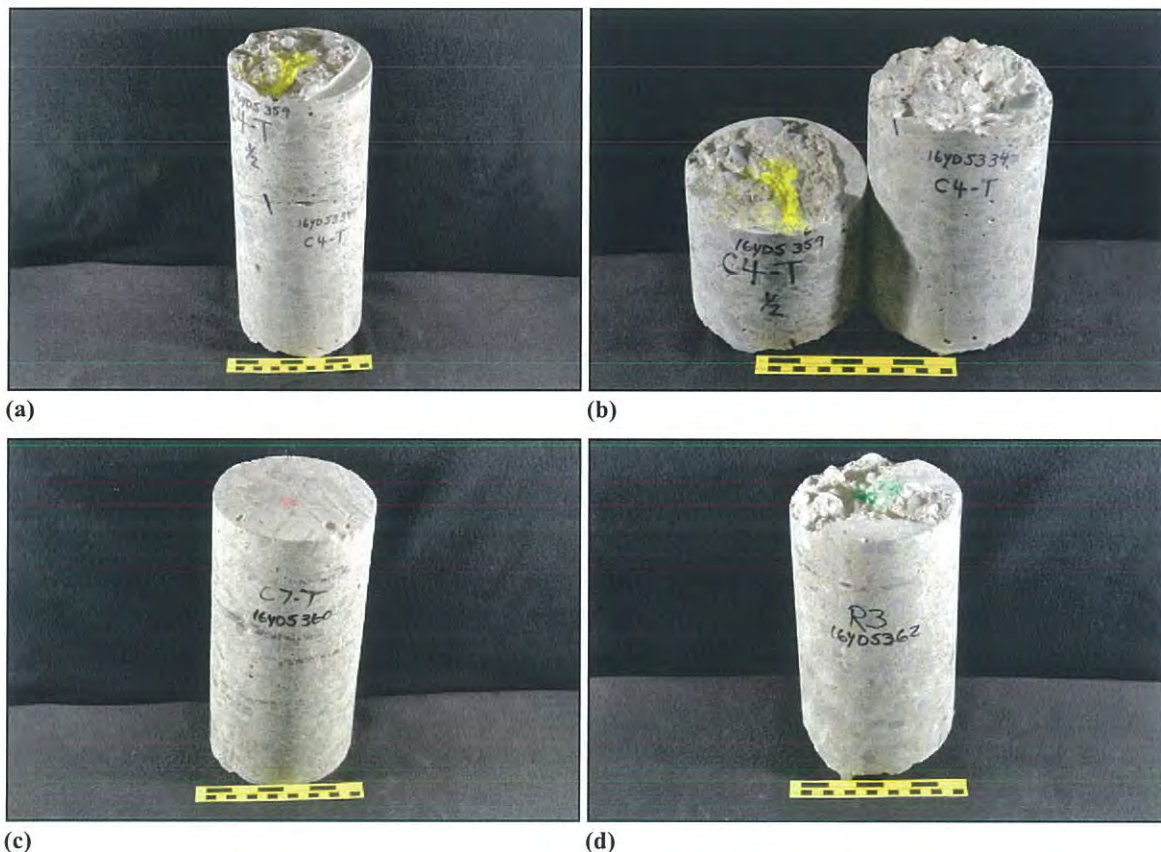


Figure 1. Photographs of some cores in as-received condition. Core C4 T showing two pieces (a) restored to original configuration and (b) as-received in separate shipments. (c) Core C7 T, which was the longest core received as one piece and which had saw-cuts at both ends. (d) Core R3 in as-received condition. Note combination of fracture and saw-cut surfaces on C4 T $\frac{1}{2}$ and R3.

3.2 As-Received Fracture Surfaces The as-received fracture surfaces consistently cut predominantly around aggregate particles. Fresh fracture surfaces, induced in the laboratory during the petrographic examinations, also cut consistently around aggregate particles. Some of the as-received surfaces were relatively clean, consistent with forming recently (perhaps during core extraction or handling) and some were covered with a film of mud or debris, suggesting they were exposed to the elements for a prolonged period of time, covered with drilling mud during the coring, or both (**Figure 2**).

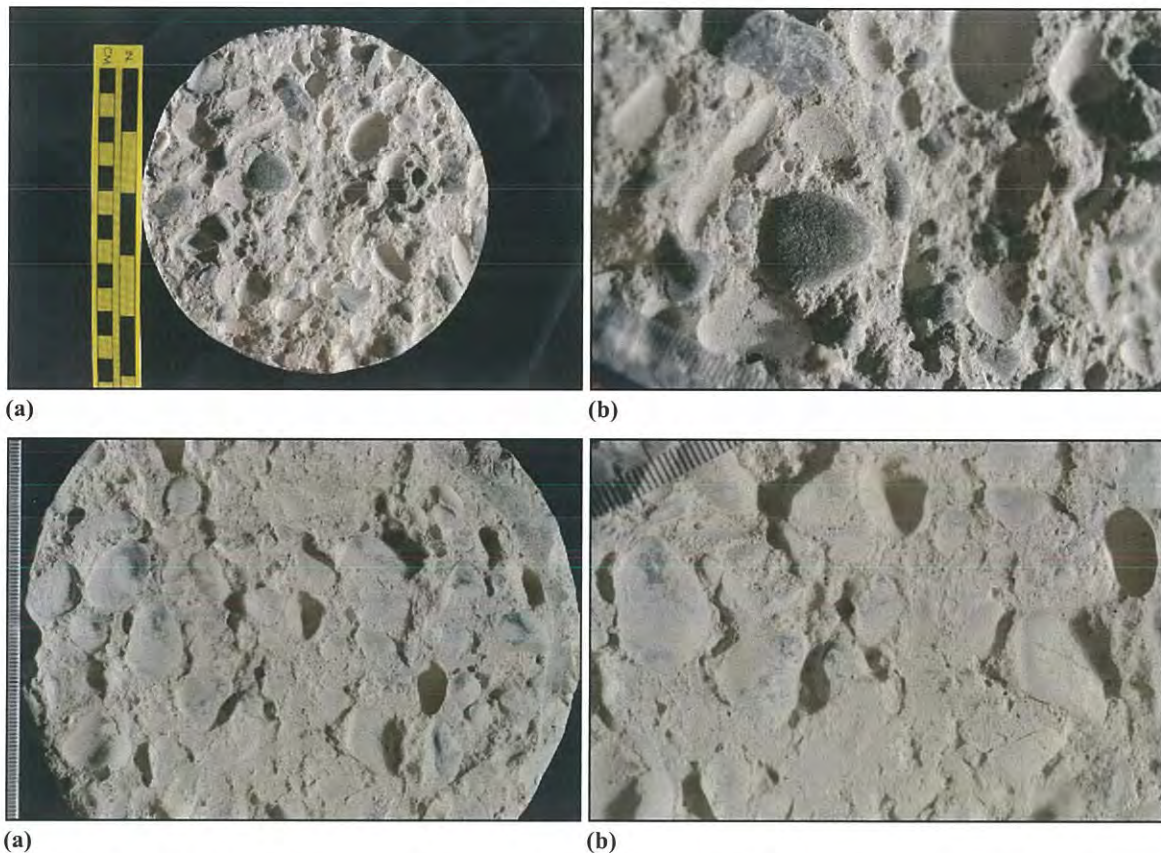


Figure 2. Photographs of as-received fracture surfaces. Photos (a) and (b) show overview and detail of as-received fracture surface at the bottom of Core C4 B, which was relatively clean. Note the clean aggregate particles exposed by the surface and the aggregate sockets. Photos (c), (d) show Core C1 T ½ showing a fracture surface that was covered with drilling mud or other detritus. The scale in (b), (c) and (d) is in millimeters.

3.3 Constituents: Paste The constituents that make up the paste in all the cores are similar. The paste fraction of the concrete consists of hydrated portland cement; no fly ash, slag cement or other supplemental cementitious materials were observed. Optical and physical properties of the cement paste were observed and documented to evaluate the quality of the paste, which is generally determined by the ratio of water to cementitious materials (w/cm). These properties include the color, texture, luster and hardness of the paste, the size and density of relict and residual cement grains, and the size and morphology of crystals of calcium hydroxide. This work identified distinct differences in the properties of the paste in different cores (**Figure 3, 4**). Cores C1, C7 T, and C12 B are similar and have properties that are typical of non-air-entrained concrete with a 28-day compressive strength (f'_c) of ~ 25 MPa. Core C4 represents the lower end of the range and has properties more typical of non-air-entrained concrete with $f'_c \sim 35$ MPa. The remaining cores represent the middle of the range, including Core R3, which was air-entrained (see below).

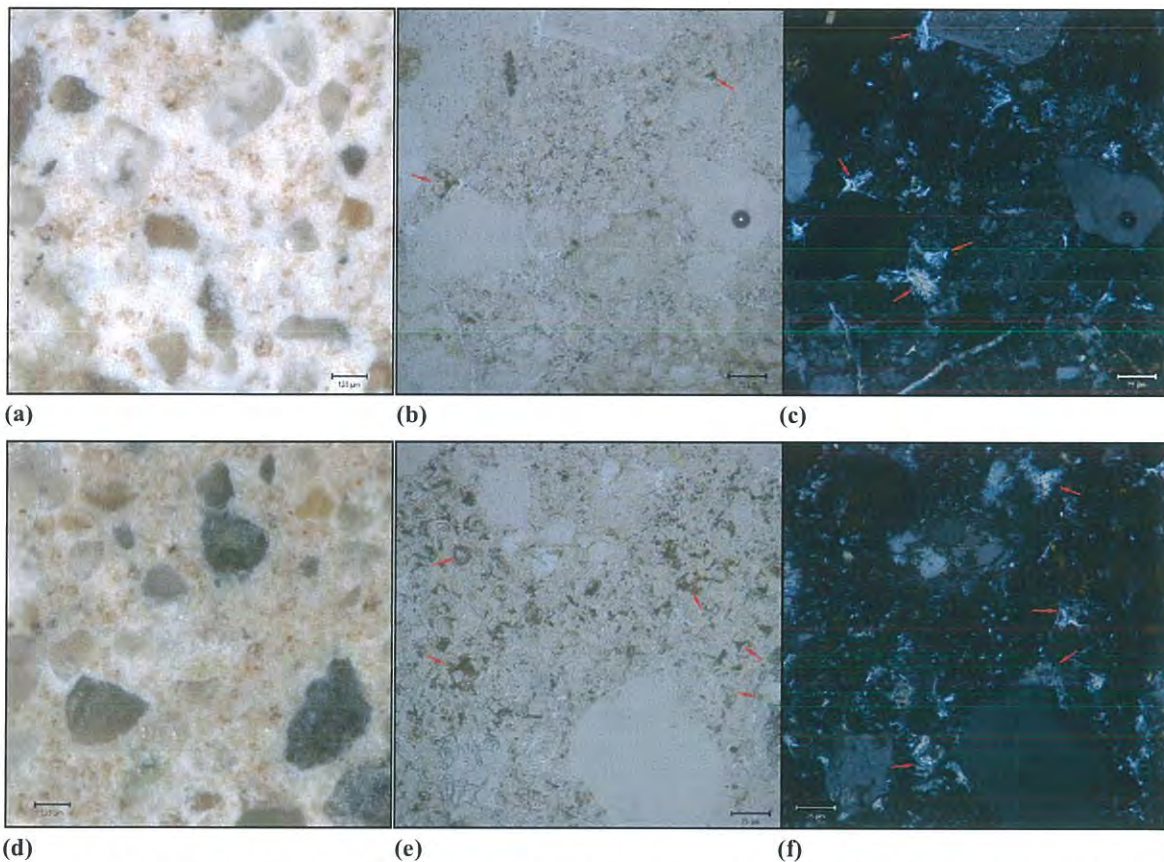


Figure 3. Paste photomicrographs from (a)-(c) Core C1 B, which had the higher w/cm typical of ~ 25 MPa concrete and (d)-(f) Core C4 B, which had the lower w/cm typical of ~ 35 MPa concrete. (a), (d) Reflected light photomicrographs of polished surface showing detail of paste color, texture and luster. (b), (e) Plane-polarized and (c), (f) cross-polarized transmitted light photomicrographs of thin sections showing detail of paste. Red arrows in (b) and (e) indicate relict and residual cement grains while the red arrows in (c) and (f) indicate calcium hydroxide.

3.4 Constituents: Air All of the cores lack air entrainment and have less than 2% total air with the exception of Core R3, which contains 4.6% total air (Table 2; Figure 4). All of the cores showed good consolidation with no significant bleed voids or large entrapped voids observed. Deposits of ettringite ranging from trace to minor amounts were observed in all the cores. The cores with the most significant deposits of ettringite in voids were C1 B ½ and C12 B ½.

Table 2. Summary of Microscopical Air Content Determinations

	C1 T ½	C4 T ½	C7 T ½	C12 B ½	R3	R7
Aggregate Content	70.3%	69.7%	75.3%	68.6%	66.4%	71.2%
Paste Content (p)	27.7%	28.8%	23.6%	29.5%	29.0%	26.8%
Air Content (A)	2.0%	1.5%	1.0%	1.9%	4.6%	2.0%
Paste-Air Ratio (p/A)	13.9	19.6	23.0	15.6	6.3	13.5

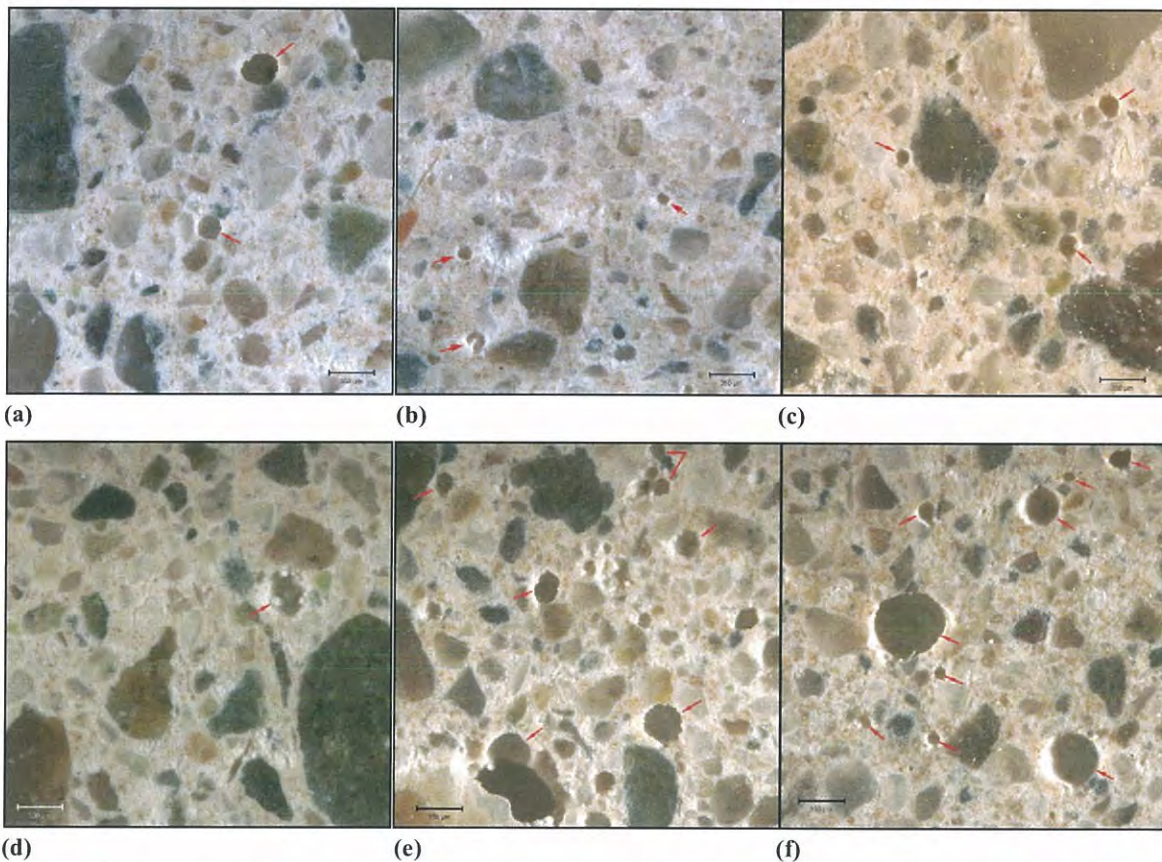


Figure 4. Oblique reflected light photomicrographs of polished surfaces of (a) C1 B ½, (b) C4 B, (c) C7 T, (d) C12 B ½, (e) R3 and (f) R7 showing voids. The red arrows show all or nearly all of the voids on the surface except in (e), where the red arrows highlight examples of voids but dark circles are also voids. This core (R3) had 4.6% total air whereas all the other cores contained less than 2% air.

3.5 Constituents: Aggregates The aggregate materials used in the production of the concrete are similar in all of the cores (**Figure 5**). The aggregates are derived from a natural glacio-fluvial source and have a nominal top size of 19 mm. The particles are sub-equant to oblong in shape and are well-rounded to sub-round. The gradation and distribution of the aggregates is somewhat variable, with some cores showing relatively high sand content and a paucity of intermediate sized aggregate particles. Some of the cores also show an alignment of the elongated (oblong) particles. The rocks are hard and competent and are siliceous in composition. Metagraywackes, which are relatively fine-grained metasedimentary rocks consisting primarily of quartz, feldspar and micaceous minerals, make up most of the aggregate. Other components include minor amounts of granitic rocks and minor to trace amounts of quartzite and more mafic igneous rocks such as granodiorite and diorite. Many of these rock types are potentially susceptible to alkali-silica reaction (ASR) but no evidence of such reactions was observed in any of the cores. The fine aggregate is a natural river sand consisting of rock types that are similar to those observed in the coarse aggregate. This indicates the sand is derived from a geological source that is similar to the coarse aggregate.

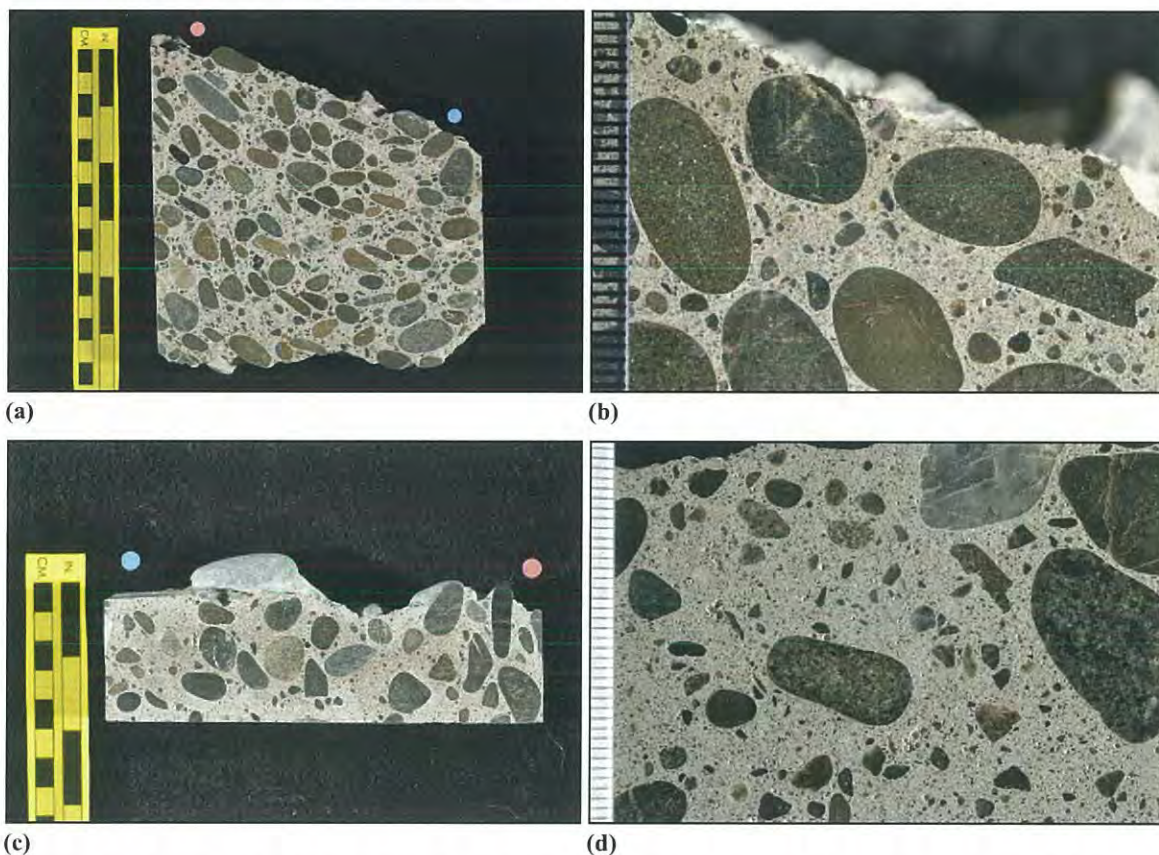


Figure 5. Photographs of the polished surfaces of (a), (b) Core C1 T $\frac{1}{2}$ and (c), (d) Core R3 showing the well-rounded nature of the river gravel. Note the tighter particle packing, alignment of aggregates and more even gradation in C1 T $\frac{1}{2}$ and the lack aggregate alignment and poor gradation (high sand content) in R3.

3.6 Aggregate Sockets Examination of the polished surfaces of the cores did not reveal deleterious coatings or incrustations directly on the aggregate particles and no low w/cm mortar coatings, which typically indicate retempering, were observed. While most aggregate sockets were very clean, occasionally sand grains were observed lining aggregate sockets on fresh fracture surfaces (**Figure 6**). This indicates that some aggregate particles were dirty, which can diminish the strength of paste-aggregate bonding, particularly when the aggregates are well-rounded.

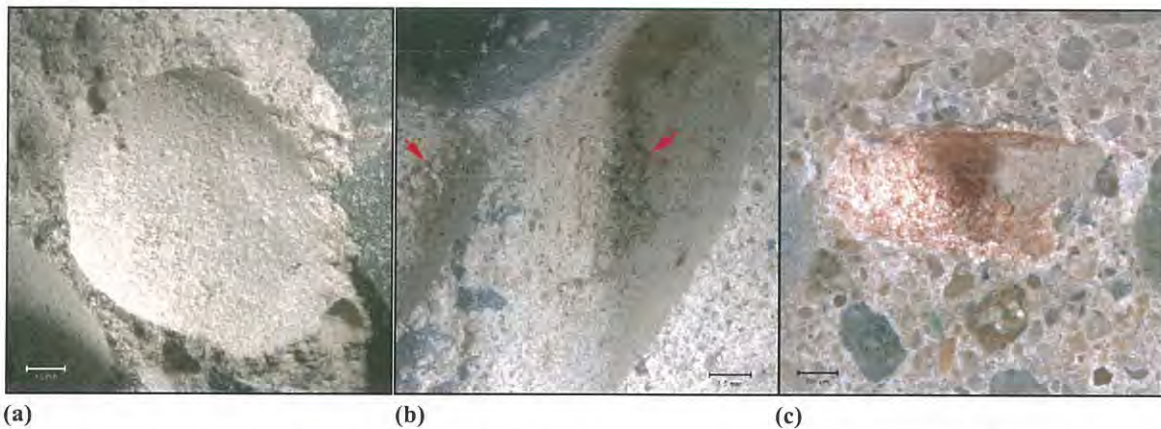


Figure 6. Reflected light photomicrographs showing various aggregate sockets. (a) Clean socket on fresh fracture surface in Core C7 T. (b) Aggregate socket on fresh fracture surface on Core C1 B ½ showing sand grains (red arrows) lining a portion of the socket. (c) Aggregate socket on polished surface of Core C4 B showing a lining of red granular sand.

3.7 Cracking & Microcracking The cores showed a lack of significant microcracking. While occasional cores showed macroscopic cracks (visible with the naked eye) that ranged from 100-250 μm wide, these were easily recognized and removed when the cores were trimmed for strength testing. These cracks consistently passed around aggregate particles and lacked secondary deposits (**Figure 7**). A few cores showed very fine, randomly oriented microcracks that were generally less than 50 μm wide and 2 mm long and consistently cut around aggregate particles. Cores where microcracks were observed included C1 T ½, C4 T, C12 B ½, and R3 (**Figure 8**). The microcracks in Cores C1-T ½, C12 B ½ and R3 contained secondary deposits of ettringite. Deposits of ettringite in this situation are significant because they form in portland cement concrete that is exposed to moisture for a prolonged period of time. This suggests the microcracks with ettringite formed prior to the recent extraction of the cores from the columns by ARC. The cracks and microcracks that lacked secondary deposits most likely formed during the coring or subsequently during the handling of the cores. Peripheral microcracking was observed along the rims of aggregate particles in Core C7 T; these did not extend into the paste.

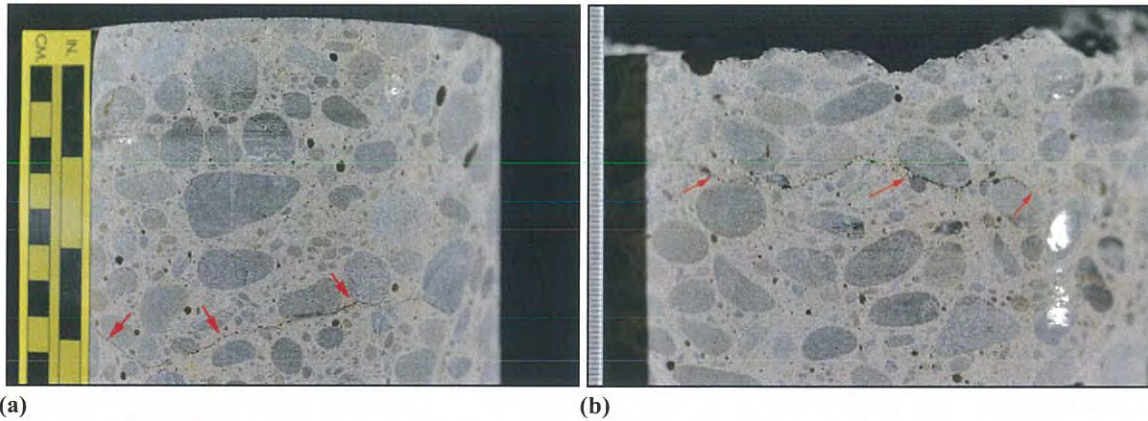


Figure 7. Photographs of hairline cracks (red arrows) observed on the sides of (a) Core C4 B and (b) Core C1 T 1/2. Scale in millimeters in (b).

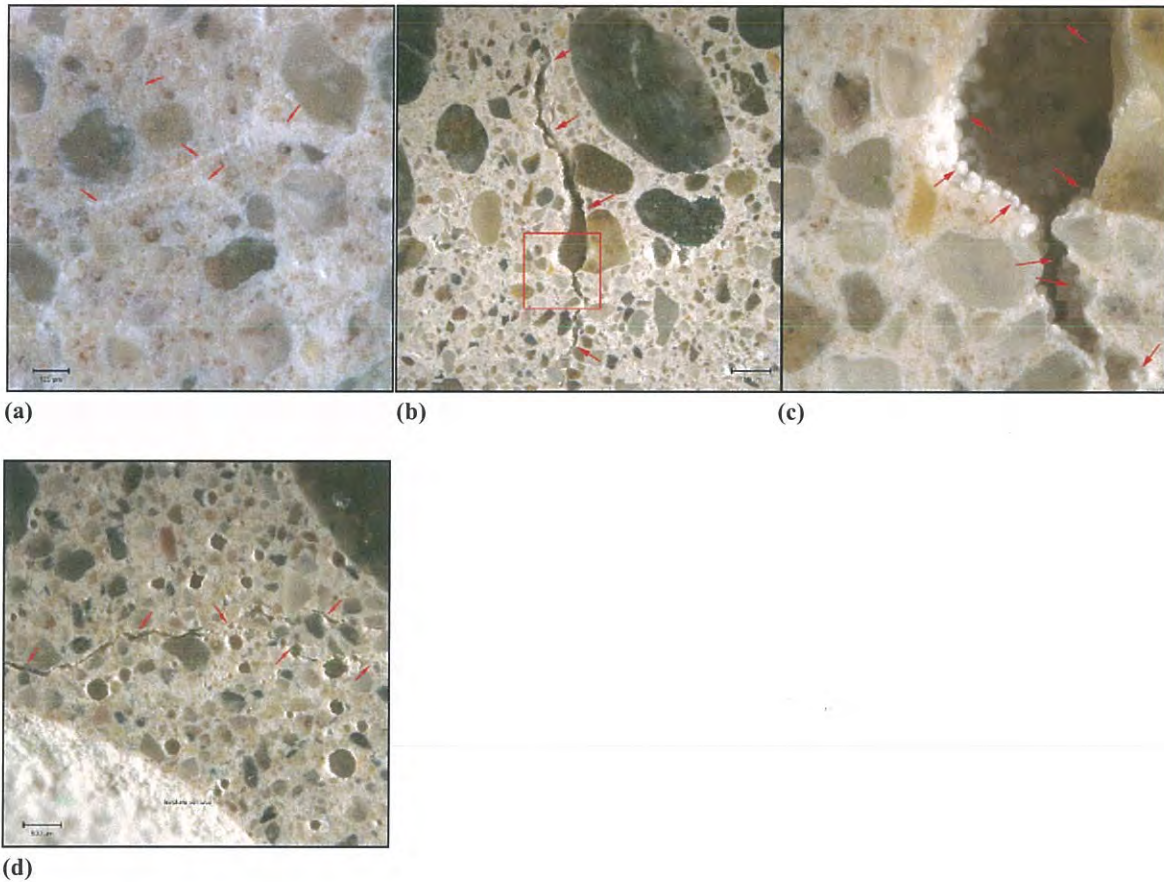


Figure 8. Reflected light photomicrographs of polished surfaces showing microcracks (red arrows). (a) Core C4 T 1/2 (b) Core C12 B 1/2; the red square in (b) indicates the approximate area of (c), where red arrows highlight rosettes of ettringite. (d) Core R3, where the microcrack occurs proximal to the as-received fracture surface.

3.8 Fire Damage Because fires were present at the CTV collapse site; the potential for fire damage to concrete was a concern for the present investigation, particularly as such damage would have a potentially adverse effect on tests aimed at understanding the physical properties of the concrete. No evidence of fire damage was observed in the present investigation. No paste discoloration or other evidence of mineralogical changes in the cement paste that occur with fire damage, such as the breakdown of calcium hydroxide, was observed. No microcracking swarms, which typically form sub-parallel to the fire-exposed surface, were observed.

3.9 Secondary Deposits No significant secondary deposits were observed in the cores aside from the ettringite observed in voids and occasional microcracks described above. None of the cores show evidence of significant carbonation, as indicated by both phenolphthalein staining (**Figure 9**) and thin section analysis.

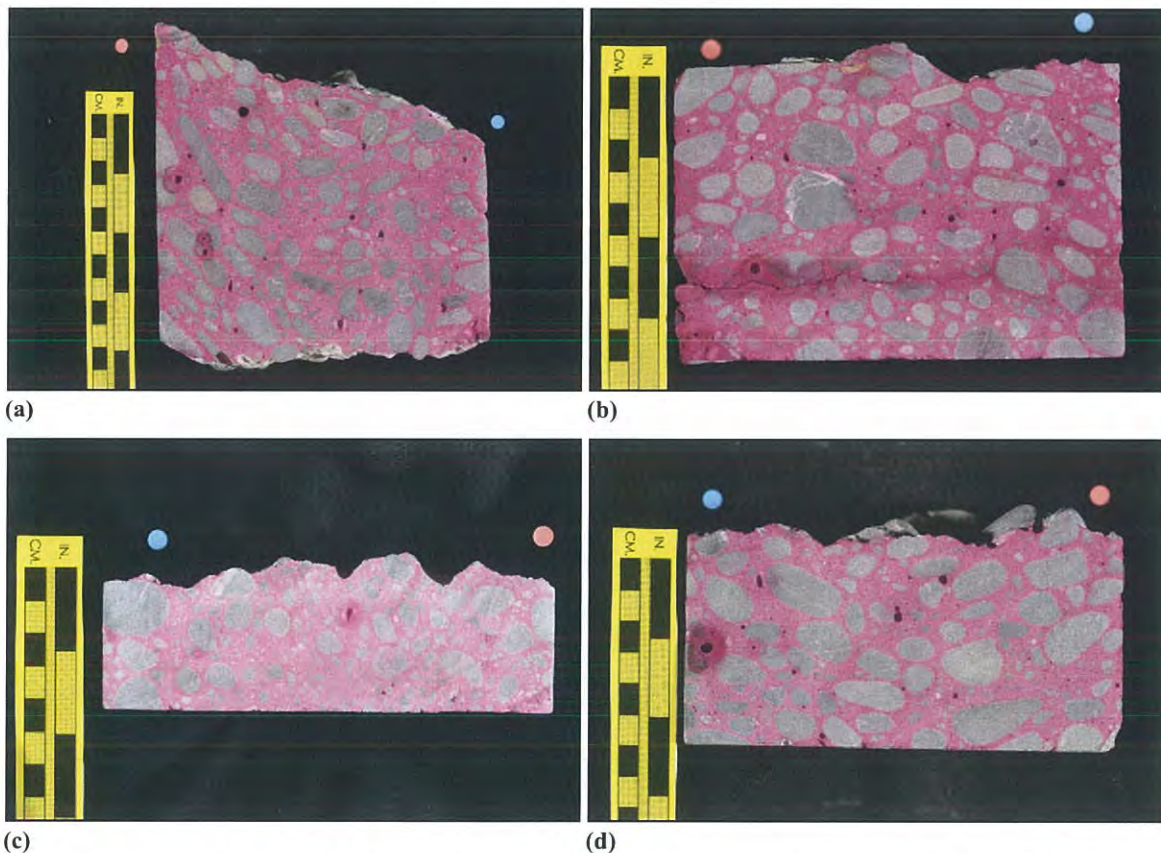


Figure 9. Photographs of phenolphthalein stained surfaces from (a) Core C1-T 1/2, (b) Core C4 B, (c) Core C12 B 1/2, and (d) Core R-7.

5.0 CONCLUSIONS

The findings described above indicate that the constituents used to produce the concrete represented by the samples are broadly consistent. The paste fraction of the concrete represented by the cores consist of hydrated portland cement with no fly ash, slag cement or other supplemental cementitious materials observed. The aggregates are siliceous in composition and have a nominal top size of 19 mm. None of the cores are air-entrained except Core R3, which contains 4.6% air.

The hydration of the cement is normal. Optical and physical properties of the paste indicate that the concrete represented by the cores was proportioned with a range of water-cement ratios that are broadly consistent with the 25-35 MPa 28-day design strengths indicated for the columns.

The rocks that make up the aggregates are hard and competent and consist primarily of metagraywackes with minor granitic rocks. The particles are well rounded to sub-round and a few cores showed evidence of sandy coatings in aggregate sockets. These factors may account for the passage of both as-received and fresh fractures predominantly around aggregate particles.

The cores are well consolidated with no large entrapped voids or bleed voids observed.

No evidence of fire damage was observed.

The cores do not show evidence of extensive microcracking but a few cores contain occasional microcracks that contain deposits of ettringite. Ettringite is also commonly observed in air voids. Ettringite is significant because it forms in portland cement concrete that is exposed to moisture for a prolonged period of time. Consequently, the presence of ettringite in microcracks is compelling evidence that the microcracks were present before the recent coring of the columns that provided the samples for the present investigation.

This concludes work performed on this project to date.



David Rothstein, Ph.D., P.G. FACI

CTV Building Collapse Core Petrography

Appendices

Appendix A	Core C1 B ½ Petrography (ASTM C856)
Appendix B	Core C1 T ½ Petrography (ASTM C856)
Appendix C	Core C4 B Petrography (ASTM C856)
Appendix D	Core C4 T ½ Petrography (ASTM C856)
Appendix E	Core C7 T ½ Petrography (ASTM C856)
Appendix F	Core C12 B ½ Petrography (ASTM C856)
Appendix G	Core R3 Petrography (ASTM C856)
Appendix H	Core R7 Petrography (ASTM C856)
Appendix I	Microscopical Air Content Data (ASTM C457)
Appendix J	Procedures

APPENDIX A: CTV Building Collapse Core Petrography
 Sample ID: Core C1B ½ (16YD5331)

Report No. DRP12.960
 Date: 7 May 2012

1. RECEIVED CONDITION

ORIENTATION	Vertical core taken through center of recovered column measures 145 mm (5 ¾ in.) in diameter and 120-140 mm (4 ¾-5 ½ in.) in length (Figure A1, A2). The examined section represented the lower portion of the core identified as C1B . The upper section of the core, which was 250 mm (9 ⅞ in.) long, was trimmed and tested for strength.
SURFACES	The top and bottom surfaces are fractures such that the core represents a partial thickness of the column.
GENERAL CONDITION	The concrete is hard and compact and rings lightly when sounded with a hammer. The as-received fracture surfaces at the top and bottom of the core cut around aggregate particles (Figure A3). The bottom surface was covered with more mud or fine detrital material than the top surface.

2. EMBEDDED OBJECTS

GENERAL	None observed.
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3. CRACKING

MACROSCOPIC	None observed.
MICROSCOPIC	No significant microcracking observed.

4. VOIDS

VOID SYSTEM	Concrete is not air-entrained and contains less than 3% air by visual estimation (not determined following ASTM C457; Figure A4). The consolidation of the concrete is good with no large entrapped voids or bleed voids observed. Occasional entrapped voids are present that range up to 3 mm (⅛ in.) across.
VOID FILLINGS	Voids occasionally contain deposits of ettringite.

5. COARSE AGGREGATE

PHYSICAL PROPERTIES	Natural river gravel with 19 mm (¾ in.) nominal top size (Figure A5). The rocks are hard and competent. The particles are mostly oblong in shape with well-rounded to round edges but sub-equant, rounded particles are also make up a significant portion of the aggregate. There is a weak alignment of elongated particles in different sections of the core. The grading is fairly even; the distribution is somewhat uneven with a vibration channel observed.
ROCK TYPES	The aggregate is siliceous in composition and consists primarily of metagraywackes with minor amounts of granitic rocks. Other components include quartzites and more mafic igneous rocks such as granodiorite and diorite. The metagraywackes are distinguished by very fine grained matrices and angular to sub-angular particles of feldspar and quartz. The quartzites are commonly medium-grained and range in composition from arenitic to arkosic. Many of these components are potentially susceptible to alkali-silica reaction (ASR).
OTHER FEATURES	No deleterious coatings or incrustations observed. No low w/c mortar coatings observed. No reaction rims, significant internal microcracking, deposits of gel or other evidence of ASR observed.

APPENDIX A: CTV Building Collapse Core Petrography
 Sample ID: Core CIB ½ (16YD5331)

Report No. DRP12.960
 Date: 7 May 2012

6. FINE AGGREGATE

PHYSICAL PROPERTIES	Natural river sand consists of rocks that are hard and competent (Figure A6). The particles are sub-equant to oblong in shape with sub-rounded to sub-angular edges. The grading and distribution are relatively even.
ROCK TYPES	The sand is mostly siliceous in composition and consists of rocks similar to those observed in the coarse aggregate, suggesting they are derived from a common geological source. The finer sieve sizes contain particles of quartz, feldspar, biotite and metallic oxide minerals.
OTHER FEATURES	No deleterious coatings or incrustations observed and no low w/c mortar coatings observed. No evidence of ASR observed.

7. PASTE OBSERVATIONS

POLISHED SURFACE	Paste is light gray (Munsell 10YR/7/2) when viewed macroscopically but is mottled from white to light brown when viewed at high magnification under reflected light. The paste has a granular to smooth texture and a sub-vitreous luster (Figure A7) and is moderately soft (Mohs ~ 3).
THIN SECTION*	The paste contains hydrated portland cement; no fly ash, slag cement or other SCM were observed (Figure A8). The hydration is advanced with less than 3% RRCG that consist mostly of belite and interstitial aluminate and ferrite. CH makes up 15-25% of the paste, is coarse-grained and unevenly distributed.
FRESH FRACTURE SURFACE	Fracture surface is light gray, has a granular texture and a dull luster. Sand lenses observed in occasional voids suggest dirty aggregate (Figure A9).
* Abbreviations as follows: RRCG = relict and residual cement grains; SCM = supplemental cementitious materials; CH = calcium hydroxide; ITZ = interfacial transition zone. Modal abundances are based on visual estimations.	

8. SECONDARY DEPOSITS

PHENOLPHTHALEIN	Entire surface stains purple (Figure A10).
DEPOSITS	Deposits of ettringite observed in occasional voids. No carbonation observed.

FIGURES



Figure A1. Photographs showing (a) oblique view of the top and side of the core with identification labels and (b) the top of the core. The red and blue dots in (a) show the orientation of the saw cuts used to prepare the sample.



Figure A1 (cont'd). (c) Photograph showing the bottom surface of the core. (d) Photograph showing both sections of the core designated as C1-B. The section that was the subject of the petrographic examination represented the lower portion of the core.

APPENDIX A: CTV Building Collapse Core Petrography
Sample ID: Core CIB 1/2 (16YD5331)

Report No. DRP12.960
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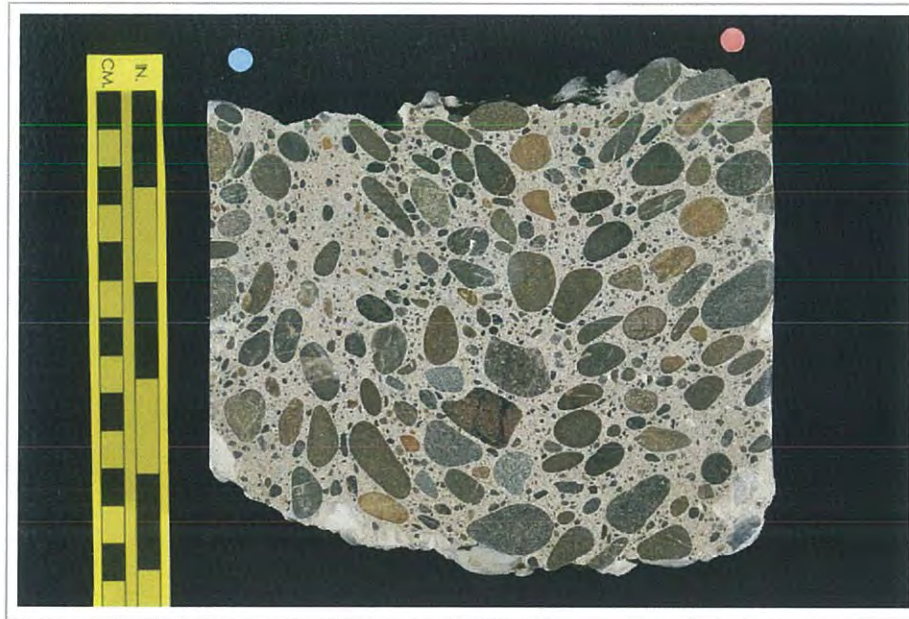


Figure A2. Photograph showing the polished surface of the core.



Figure A3. Photograph showing detail of the top surface of the core; scale in millimeters.

APPENDIX A: CTV Building Collapse Core Petrography
Sample ID: Core CIB 1/2 (16YD5331)

Report No. DRP12.960
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Figure A3 (cont'd). Photograph showing detail of the bottom surface of the core; scale in millimeters.

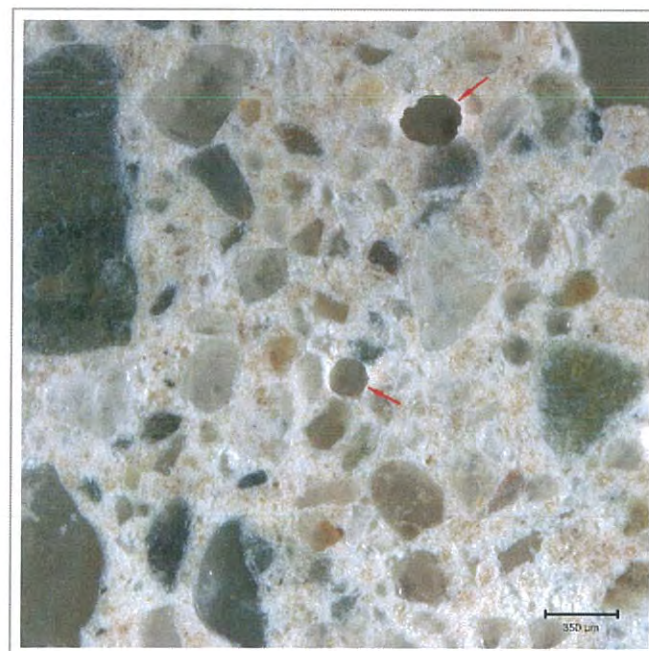


Figure A4. Oblique reflected light photomicrograph of polished surface showing voids (red arrows highlight examples).



Figure A5. Photograph of the polished surface showing coarse aggregate; scale in millimeters.

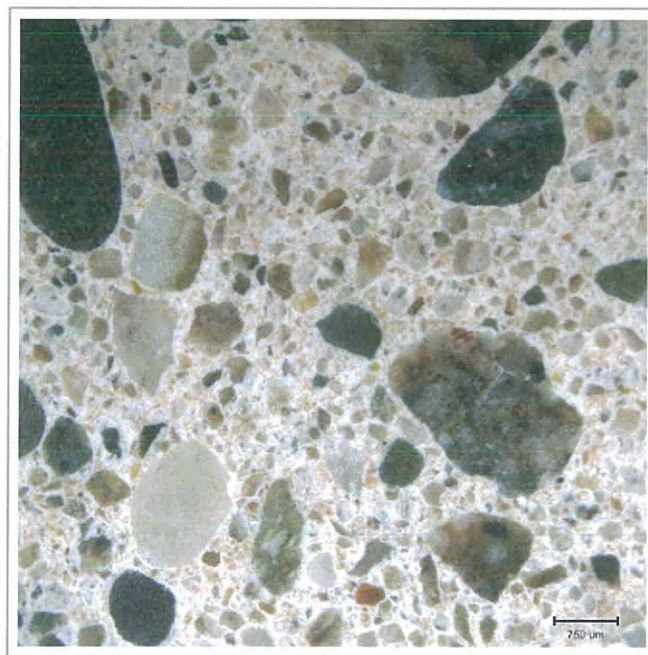


Figure A6. Reflected light photomicrograph of polished surface showing the fine aggregate.

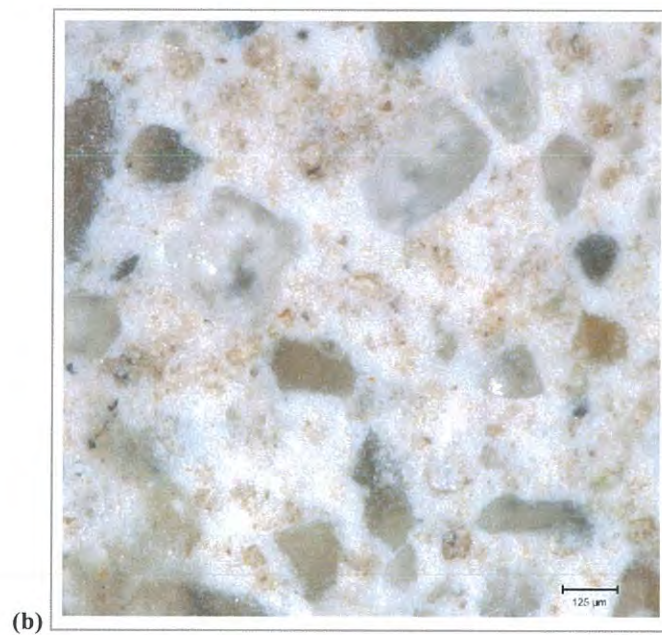


Figure A7. (a) Photograph of polished surface showing overview of paste in the middle of the core. The scale is in millimeters. (b) Reflected light photomicrograph of polished surface showing detail of paste texture and luster.

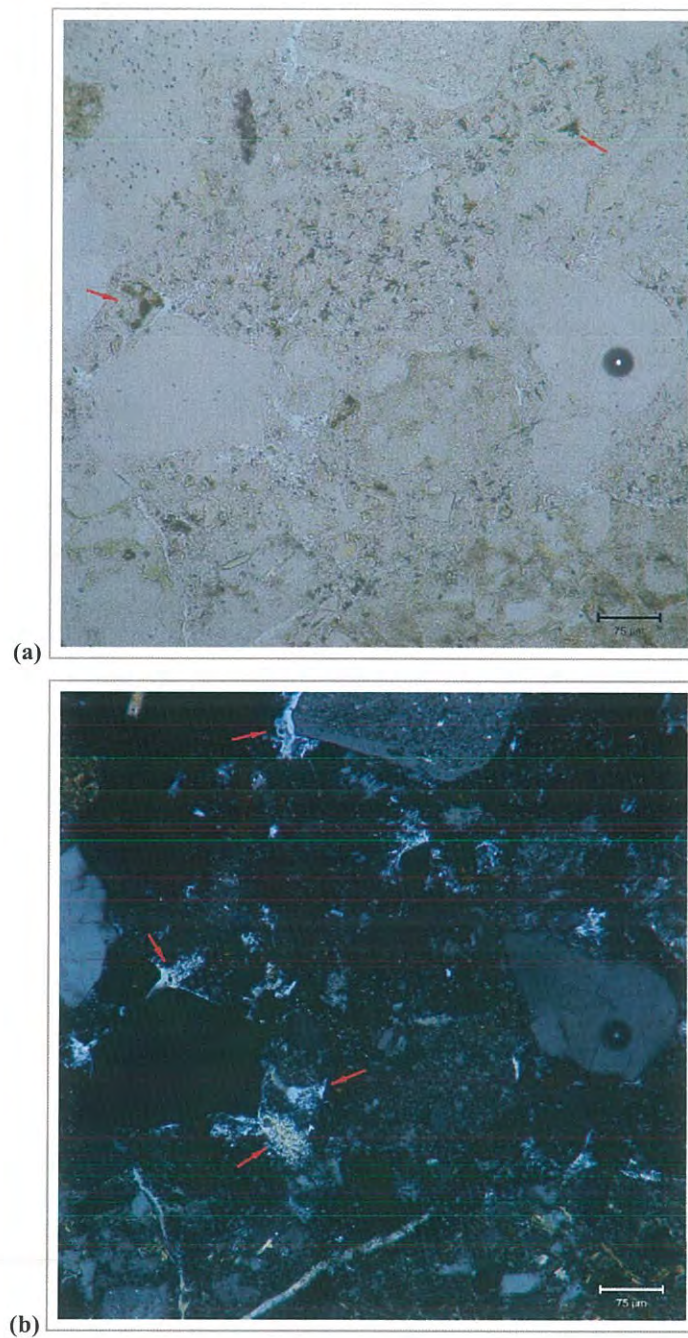


Figure A8. Transmitted light photomicrographs of thin section from the concrete core showing detail of paste in (a) plane-polarized and (b) cross-polarized light. The red arrows in (a) indicate RRCG; in (b) they indicate CH.

APPENDIX A: CTV Building Collapse Core Petrography
Sample ID: Core CIB 1/2 (16YD5331)

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Figure A9. Reflected light photomicrograph of a fresh fracture surface showing two aggregate sockets that contained sand grains (red arrows).

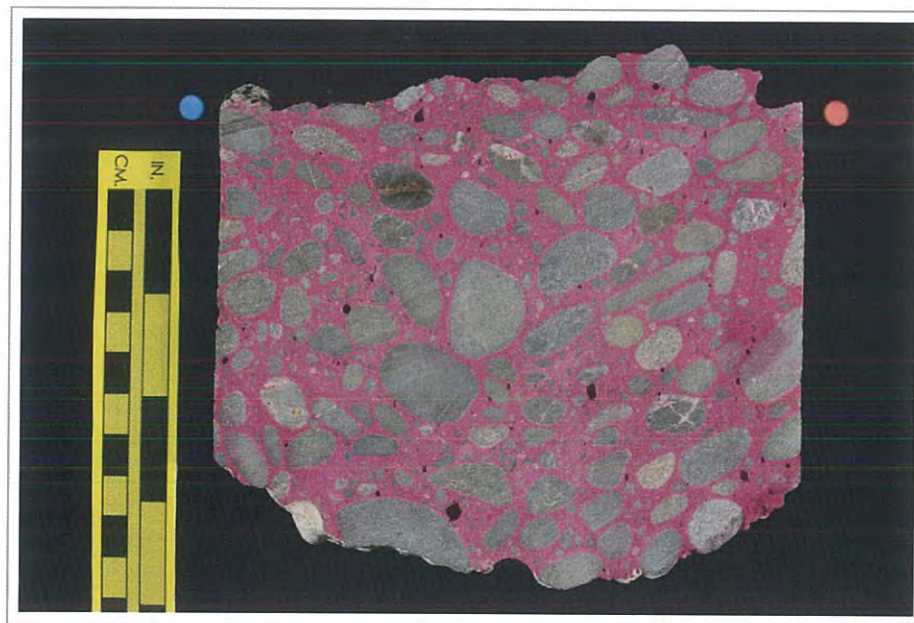


Figure A10. Photograph showing phenolphthalein stained surface.

APPENDIX B: CTV Building Collapse Core Petrography
 Sample ID: Core CIT ½ (16YD5332)

Report No. DRP12.960
 Date: 8 May 2012

1. RECEIVED CONDITION

ORIENTATION	Vertical core taken through center of recovered column measures 145 mm (5 ¾ in.) in diameter and 95-145 mm (3 ¾-5 ¾ in.) in length (Figure B1, B2). The examined section represented the lower portion of the core identified as CIT ½. The upper section of the core, which was longer (245 mm or 9 ⅝ in.), was trimmed and tested for strength.
SURFACES	The top and bottom surfaces are fractures such that the core represents a partial thickness of the column.
GENERAL CONDITION	The concrete is hard and compact and rings lightly when sounded with a hammer. The as-received fracture surfaces at the top and bottom of the core cut around aggregate particles (Figure B3). The bottom surface was covered with more mud or fine detrital material than the top surface.

2. EMBEDDED OBJECTS

GENERAL	None observed.
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3. CRACKING

MACROSCOPIC	None observed.
MICROSCOPIC	No significant microcracking observed. A few rare microcracks ranging up to 25 µm (1 mil) wide and 2.5 mm (100 mil) long were observed striking sub-horizontally through the paste (Figure B4). The microcracks contain white secondary deposits.

4. VOIDS

VOID SYSTEM	Concrete is not air-entrained and contains less than 2.0% air by ASTM C457 (Figure B5). The consolidation of the concrete is good with no large entrapped voids or bleed voids observed.
VOID FILLINGS	Voids are mostly free of secondary deposits; rare to occasional voids contain deposits of ettringite.

5. COARSE AGGREGATE

PHYSICAL PROPERTIES	Natural river gravel with 19 mm (¾ in.) nominal top size (Figure B6). The rocks are hard and competent. The particles are mostly oblong in shape with well-rounded to round edges but sub-equant, rounded particles are also make up a significant portion of the aggregate. There is a weak alignment of elongated particles in different sections of the core. The grading and distribution is fairly even.
ROCK TYPES	The aggregate is siliceous in composition and consists primarily of metagraywackes with minor amounts of granitic rocks. Other components include quartzites and more mafic igneous rocks such as granodiorite and diorite. The metagraywackes range from very fine-grained rocks to rocks that have fine grained matrices and angular to sub-angular particles of feldspar, quartz, and biotite. The quartzites are commonly medium-grained and range in composition from arenitic to arkosic. Many of these components are potentially susceptible to alkali-silica reaction (ASR).
OTHER FEATURES	No deleterious coatings or incrustations observed but many particles show brown paste along the paste-aggregate boundary (Figure B7). No low w/c mortar coatings observed. No reaction rims, significant internal microcracking, deposits of gel or other evidence of ASR observed.

APPENDIX B: CTV Building Collapse Core Petrography
 Sample ID: Core CIT 1/2 (16YD5332)

Report No. DRP12.960
 Date: 8 May 2012

6. FINE AGGREGATE

PHYSICAL PROPERTIES	Natural river sand consists of rocks that are hard and competent (Figure B8). The particles are sub-equant to oblong in shape with sub-rounded to sub-angular edges. The grading and distribution are relatively even.
ROCK TYPES	The sand is mostly siliceous in composition and consists of rocks similar to those observed in the coarse aggregate, suggesting they are derived from a common geological source. The finer sieve sizes contain particles of quartz, feldspar, biotite and metallic oxide minerals.
OTHER FEATURES	No deleterious coatings or incrustations observed and no low w/c mortar coatings observed. No evidence of ASR observed.

7. PASTE OBSERVATIONS

POLISHED SURFACE	Paste is light gray (Munsell 10YR/7/2) when viewed macroscopically but is mottled from white to light brown when viewed at high magnification under reflected light (Figure B9). The paste has a granular to smooth texture and a sub-vitreous luster and is moderately soft (Mohs ~ 3).
THIN SECTION*	The paste contains hydrated portland cement; no fly ash, slag cement or other SCM were observed (Figure B10). The hydration is advanced with less than 3% RRCG that consist mostly of belite and interstitial aluminate and ferrite. CH makes up 15-25% of the paste, is coarse-grained and unevenly distributed.
FRESH FRACTURE SURFACE	Fracture surface is light gray, has a granular to punky texture and a dull to chalky luster. The fracture cuts through ~ 20% of the aggregate particles.
* Abbreviations as follows: RRCG = relict and residual cement grains; SCM = supplemental cementitious materials; CH = calcium hydroxide; ITZ = interfacial transition zone. Modal abundances are based on visual estimations.	

8. SECONDARY DEPOSITS

PHENOLPHTHALEIN	Entire surface stains purple (Figure B11).
DEPOSITS	Deposits of ettringite observed in rare voids. No carbonation observed.

FIGURES

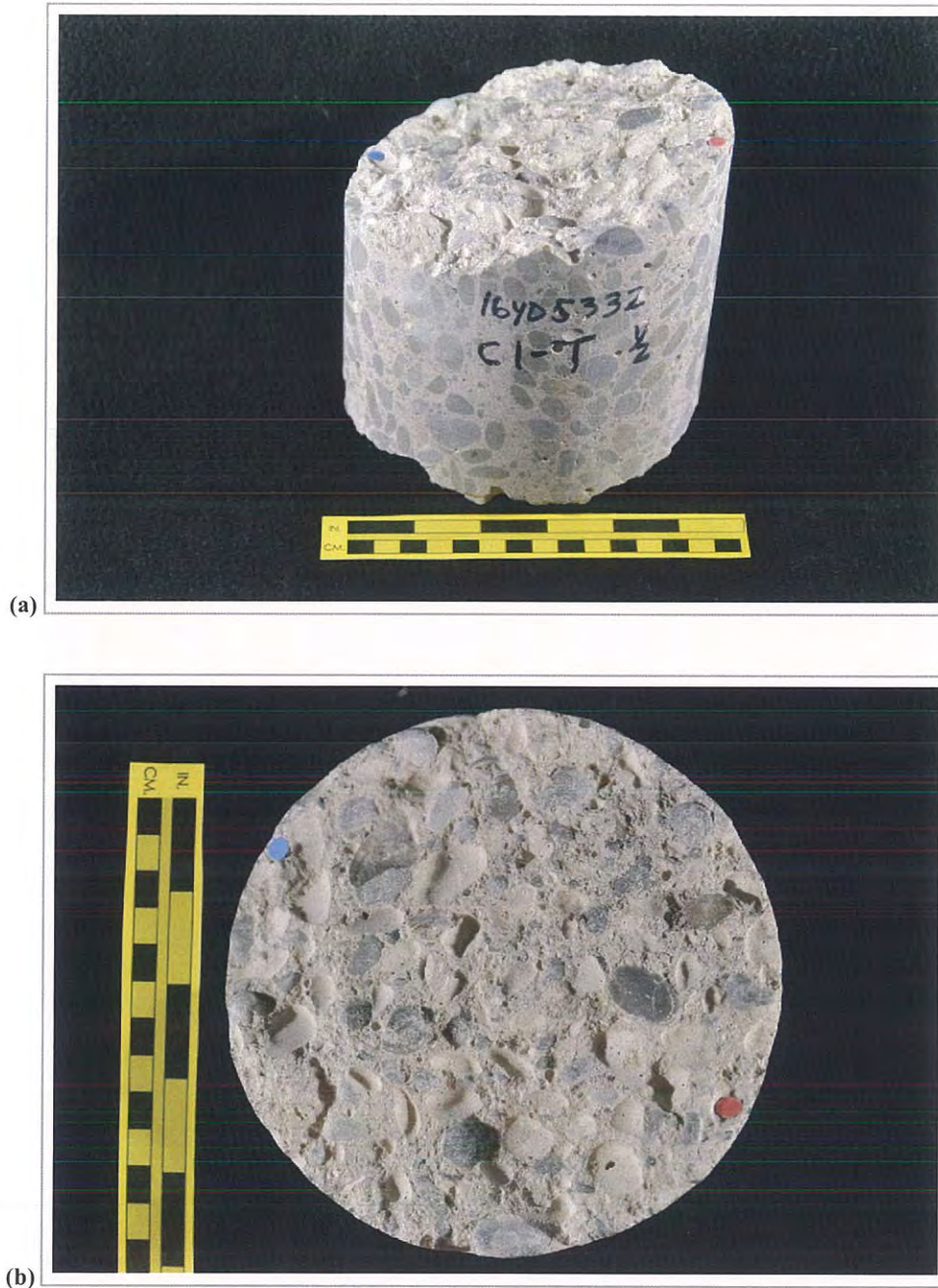


Figure B1. Photographs showing (a) oblique view of the top and side of the core with identification labels and (b) the top of the core. The red and blue dots in (a) show the orientation of the saw cuts used to prepare the sample.



Figure B1 (cont'd). (c) Photograph showing the bottom surface of the core. (d) Photograph showing both sections of the core designated as C1-T ½. The section that was the subject of the petrographic examination represented the lower portion of the core. The red arrow highlights the crack that separated the top and lower portions of the core.

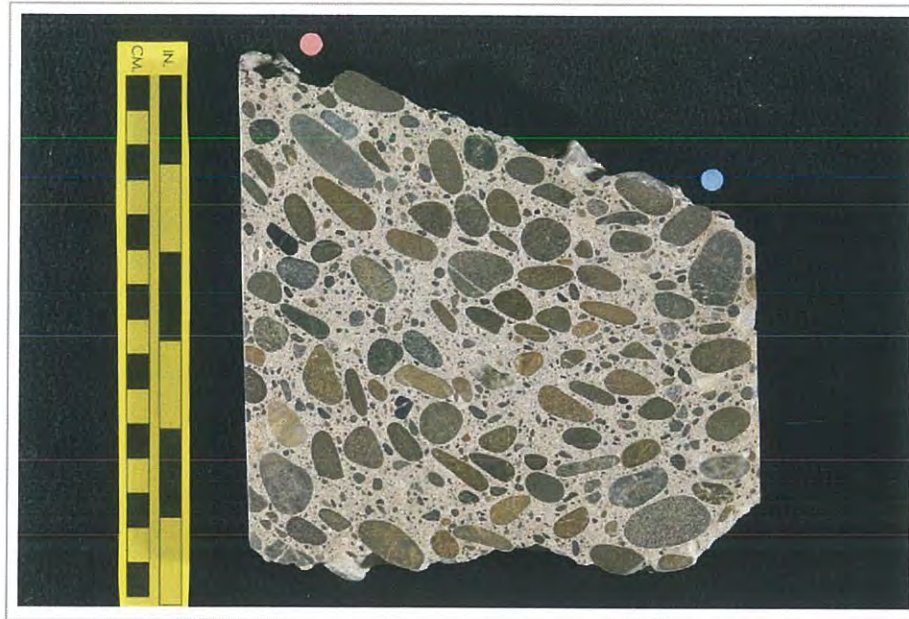


Figure B2. Photograph showing the polished surface of the core.



Figure B3. Photograph showing detail of the top surface of the core; scale in millimeters.



Figure B3 (cont'd). Photograph showing detail of the bottom surface of the core; scale in millimeters.

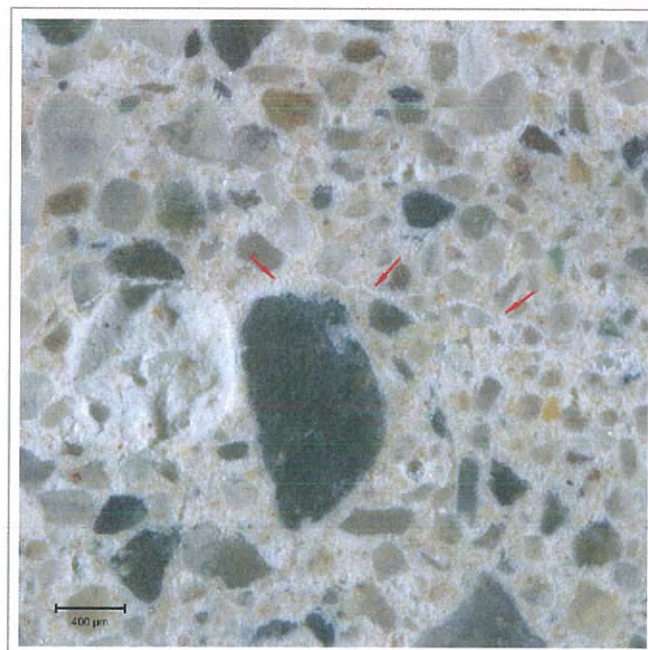


Figure B4. Reflected light photomicrograph of polished surface showing microcrack (red arrows).

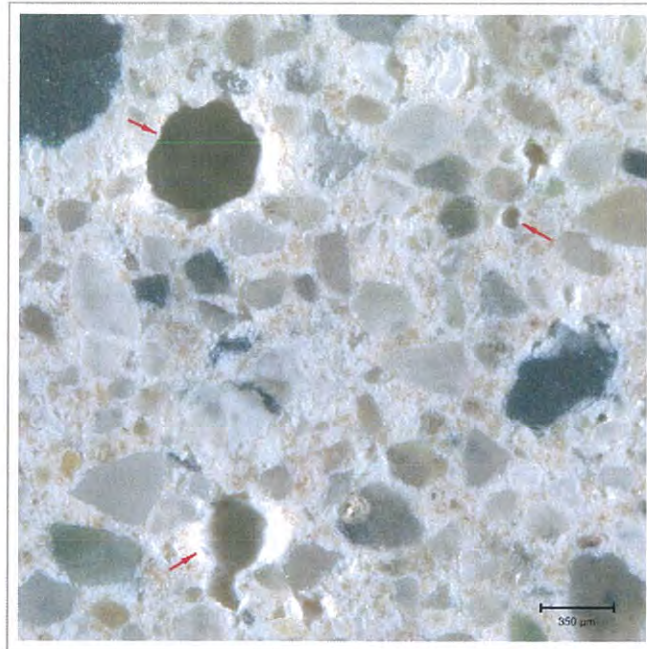


Figure B5. Oblique reflected light photomicrograph of polished surface showing voids (red arrows highlight examples).



Figure B6. Photograph of the polished surface showing coarse aggregate; scale in millimeters.

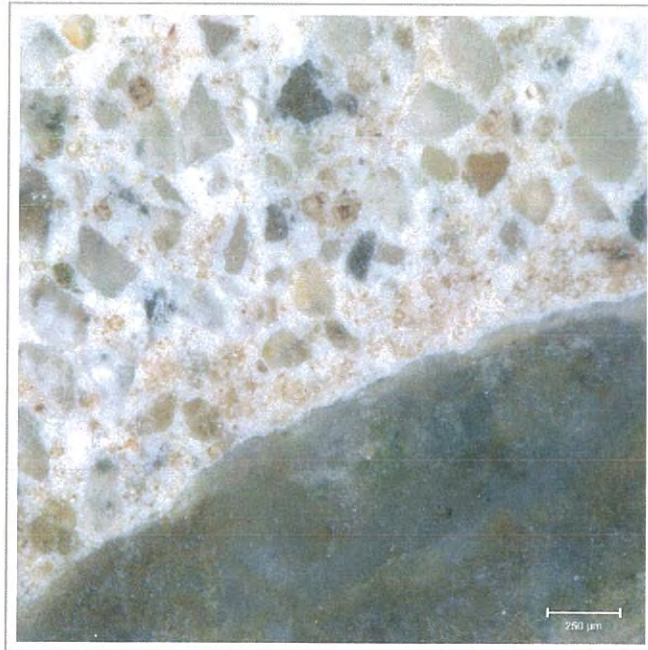


Figure B7. Reflected light photomicrograph of polished surface showing the fine aggregate.

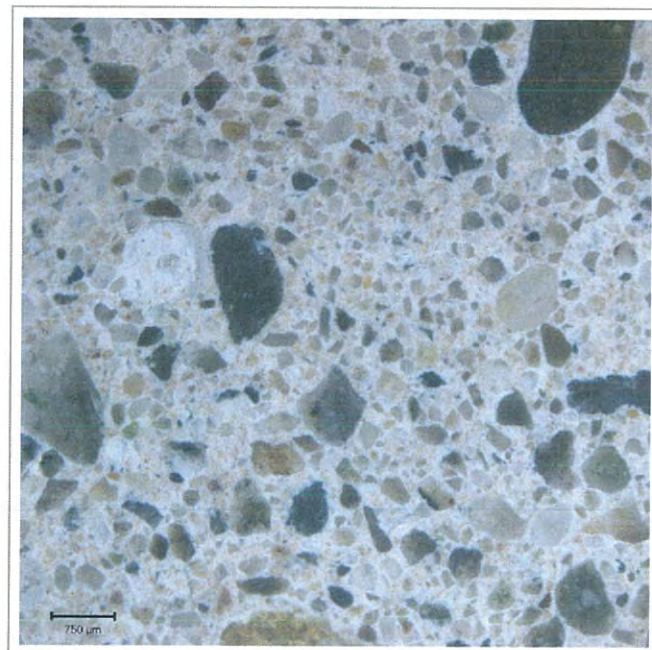


Figure B8. Reflected light photomicrograph of polished surface showing the fine aggregate.

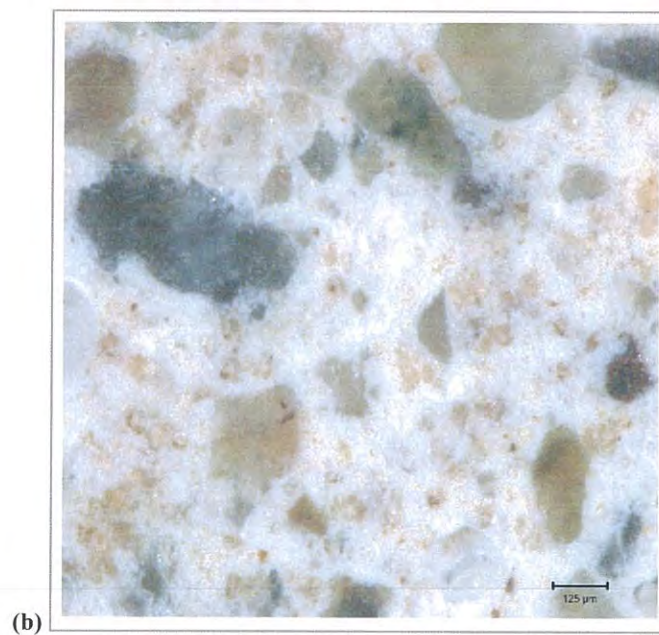


Figure B9. (a) Photograph of polished surface showing overview of paste near the lower fracture surface; the scale is in millimeters. (b) Reflected light photomicrograph of polished surface showing detail of paste texture and luster.

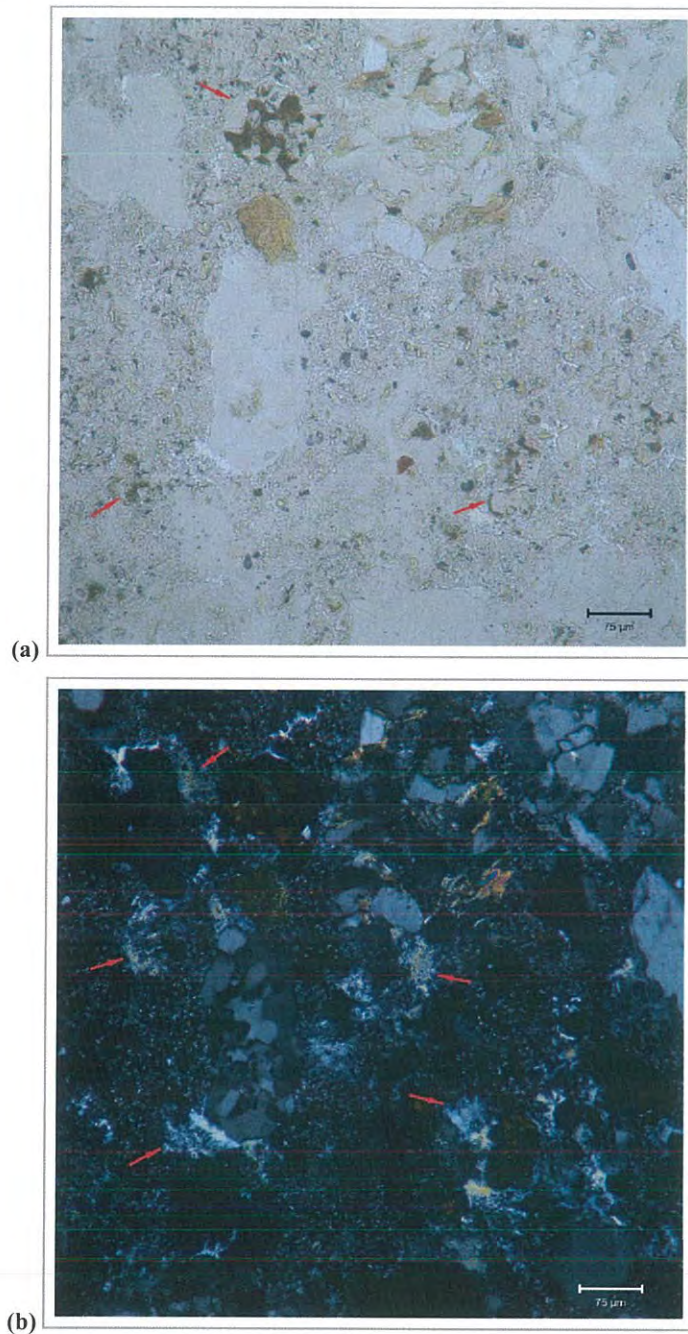


Figure B10. Transmitted light photomicrographs of thin section from the concrete core showing detail of paste in (a) plane-polarized and (b) cross-polarized light. The red arrows in (a) indicate RRCG; in (b) they indicate CH.

APPENDIX B: CTV Building Collapse Core Petrography
Sample ID: Core CIT 1/2 (16YD5332)

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Date: 8 May 2012

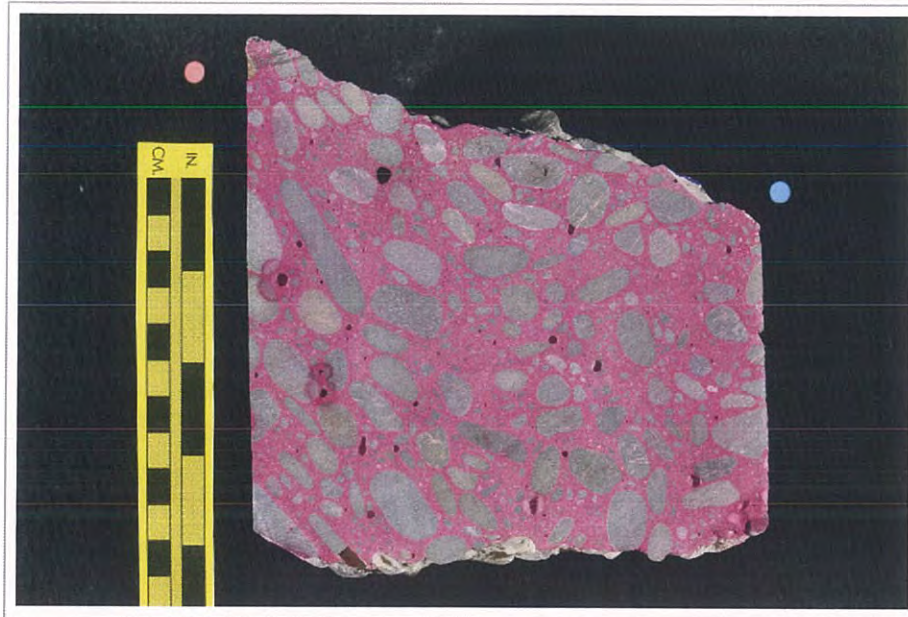


Figure B11. Photograph showing phenolphthalein stained surface.

APPENDIX C: CTV Building Collapse Core Petrography
 Sample ID: Core C4B (16YD5333)

Report No. DRP12.960
 Date: 8 May 2012

1. RECEIVED CONDITION	
ORIENTATION	Vertical core taken through center of recovered column measures 145 mm (5 ¾ in.) in diameter and 210-275 mm (8 ¼ - 10 ⅞ in.) in length (Figure C1, C2). The middle section of the core was trimmed and tested for physical properties such as compressive strength and the top section was used for petrography. Both sides of the slab cut from this section were polished.
SURFACES	The top surface is a saw cut and the bottom surface is a fracture such that the core represents a partial thickness of the column.
GENERAL CONDITION	The concrete is hard and compact and rings lightly when sounded with a hammer. The as-received fracture surface at the bottom of the core cuts around aggregate particles (Figure C3). A crack cuts sub-horizontally around the core (see below) about 75 mm (3 in.) below the top surface of the core. The core was trimmed just below this crack and the section above was used for petrography.

2. EMBEDDED OBJECTS	
GENERAL	None observed.

3. CRACKING	
MACROSCOPIC	A crack cuts around ~ 50% of the outer surface of the core about 75-85 mm (3-3 ⅞ in.) below the top of the core (Figure C4). The crack cuts exclusively around aggregate particles, ranges up to 0.5 mm (20 mil) wide and is free of secondary deposits.
MICROSCOPIC	No significant microcracking observed.

4. VOIDS	
VOID SYSTEM	Concrete is not air-entrained and contains less than 1.5% air by ASTM C457 (Figure C5). The consolidation of the concrete is good with no large entrapped voids or bleed voids observed.
VOID FILLINGS	Voids are mostly free of secondary deposits; rare to occasional voids contain deposits of ettringite.

5. COARSE AGGREGATE	
PHYSICAL PROPERTIES	Natural river gravel with 19 mm (¾ in.) nominal top size (Figure C6). The rocks are hard and competent. The particles are mostly oblong in shape with well-rounded to round edges but sub-equant, rounded particles also make up a significant portion of the aggregate. No alignment of elongated particles observed. The grading and distribution is fairly even.
ROCK TYPES	The aggregate is siliceous in composition and consists primarily of metagraywackes with minor amounts of granitic rocks. Other components include quartzites and more mafic igneous rocks such as granodiorite and diorite. The metagraywackes range from very fine-grained rocks to rocks that have fine grained matrices and angular to sub-angular particles of feldspar, quartz, and biotite. The quartzites are commonly medium-grained and range in composition from arenitic to arkosic. Many of these components are potentially susceptible to alkali-silica reaction (ASR).
OTHER FEATURES	No deleterious coatings or incrustations observed on most of polished surface but one aggregate socket showed a rust-colored sand lining (Figure C7). No low w/c mortar coatings observed. No reaction rims, significant internal microcracking, deposits of gel or other evidence of ASR observed.

APPENDIX C: CTV Building Collapse Core Petrography
 Sample ID: Core C4B (16YD5333)

Report No. DRP12.960
 Date: 8 May 2012

6. FINE AGGREGATE

PHYSICAL PROPERTIES	Natural river sand consists of rocks that are hard and competent (Figure C8). The particles are sub-equant to oblong in shape with sub-rounded to sub-angular edges. The grading and distribution are relatively even.
ROCK TYPES	The sand is mostly siliceous in composition and consists of rocks similar to those observed in the coarse aggregate, suggesting they are derived from a common geological source. The finer sieve sizes contain particles of quartz, feldspar, biotite and metallic oxide minerals.
OTHER FEATURES	No deleterious coatings or incrustations observed and no low w/c mortar coatings observed. No evidence of ASR observed.

7. PASTE OBSERVATIONS

POLISHED SURFACE	Paste is light brownish gray (Munsell 2.5Y/6/2) but is mottled from white to light brown when viewed at high magnification under reflected light (Figure C9). The paste has a smooth texture and a sub-vitreous luster. The paste is moderately hard (Mohs ~ 3.5).
THIN SECTION*	The paste contains hydrated portland cement; no fly ash, slag cement or other SCM were observed (Figure C10). The hydration is normal with 3-6% RRCG that consist mostly of belite and interstitial aluminate and ferrite. CH makes up 12-18% of the paste, is medium to coarse-grained and unevenly distributed.
FRESH FRACTURE SURFACE	Fracture surface is light gray, has a granular texture and a dull luster. The fracture cuts through ~ 25% of the aggregate particles.
* Abbreviations as follows: RRCG = relict and residual cement grains; SCM = supplemental cementitious materials; CH = calcium hydroxide; ITZ = interfacial transition zone. Modal abundances are based on visual estimations.	

8. SECONDARY DEPOSITS

PHENOLPHTHALEIN	Entire surface stains purple (Figure C11).
DEPOSITS	Deposits of ettringite observed in rare voids. No carbonation observed.

FIGURES

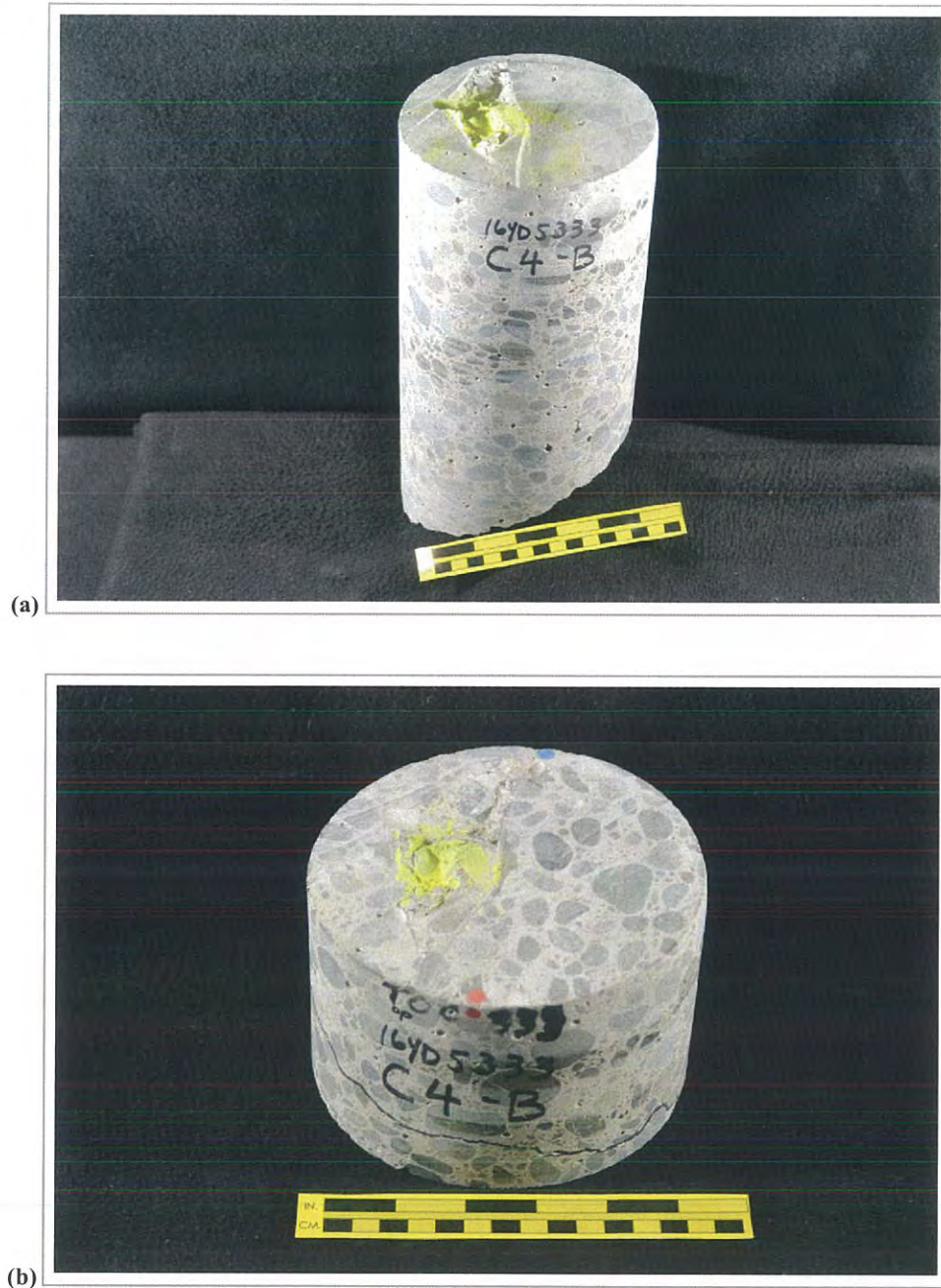


Figure C1. Photographs showing oblique views of the top and side of the core with identification labels (a) in the as-received condition and (b) after the core was trimmed for strength testing. The red and blue dots in (b) show the orientation of the saw cuts used to prepare the sample.

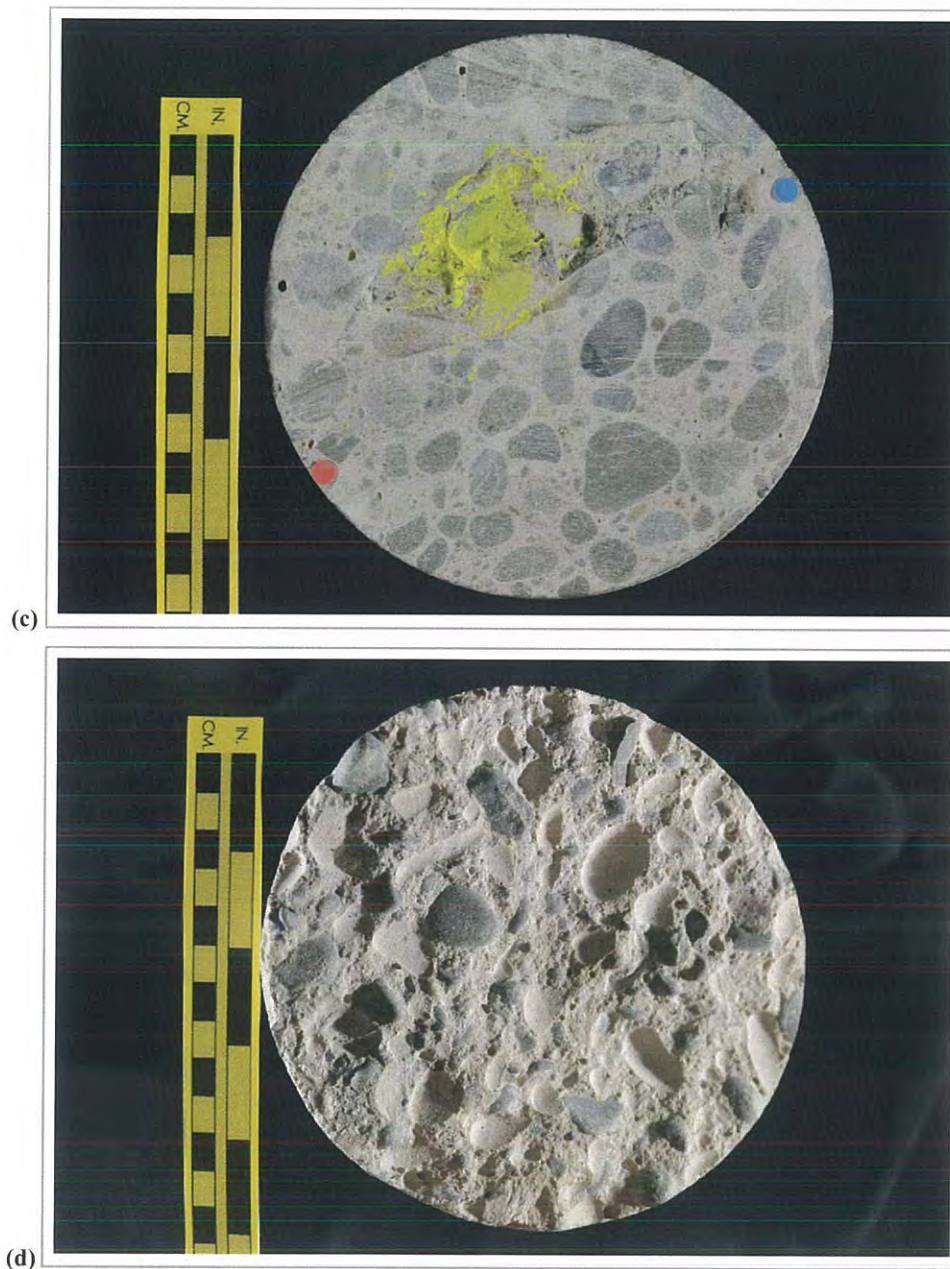


Figure C1 (cont'd). Photographs showing the (a) top and (b) bottom surfaces of the core. The red and blue dots in (a) show the orientation of the saw cuts used to prepare the polished surface of the sample.



Figure C2. Photograph showing one of the polished surfaces of the core.



Figure C3. Photograph showing detail of the bottom as-received fracture surface; scale in millimeters.

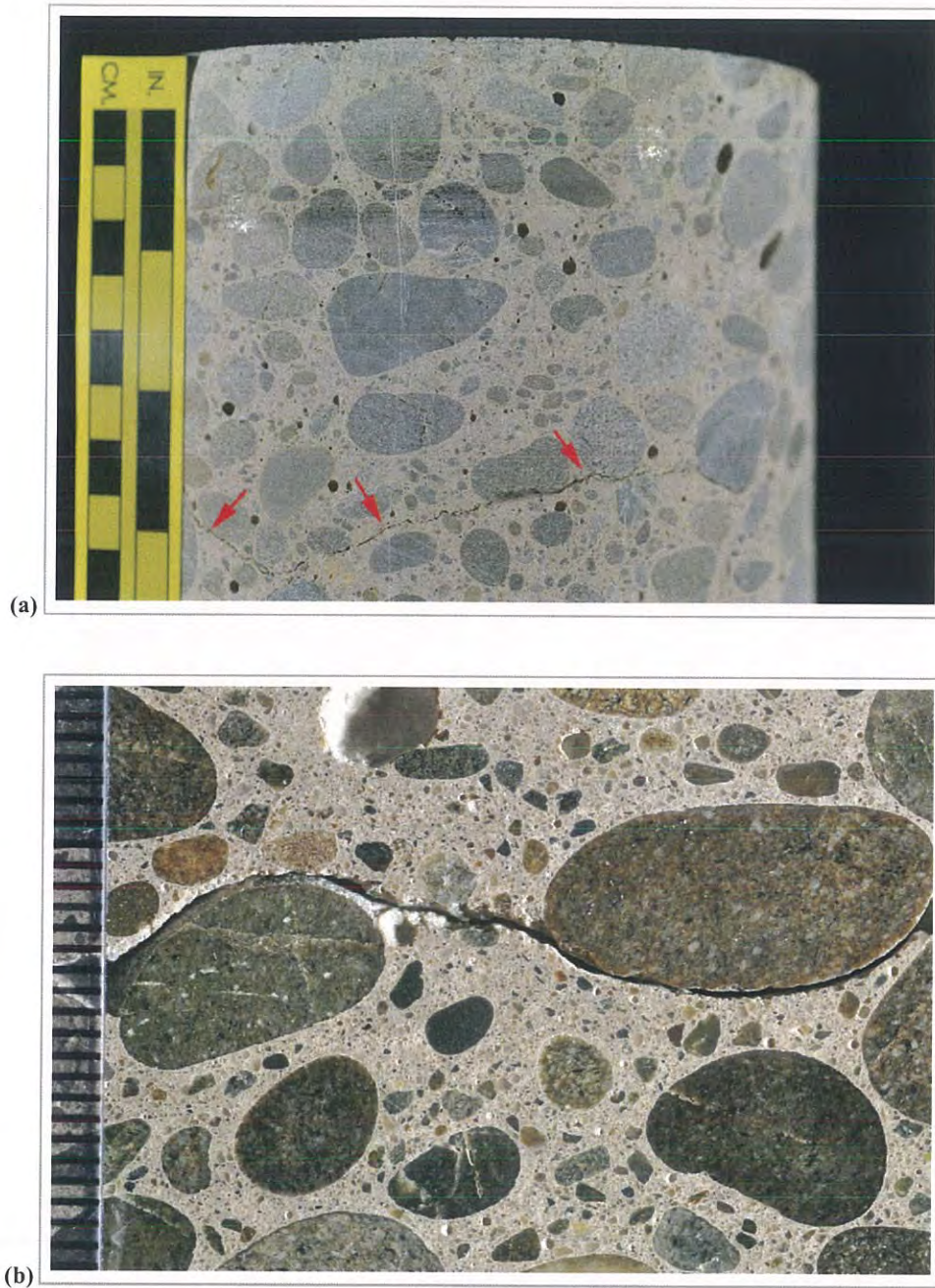


Figure C4. Photographs of (a) side of core showing sub-horizontal crack (red arrows) and (b) polished surface showing the sub-horizontal crack shown in (a). Scale in millimeters in (b).

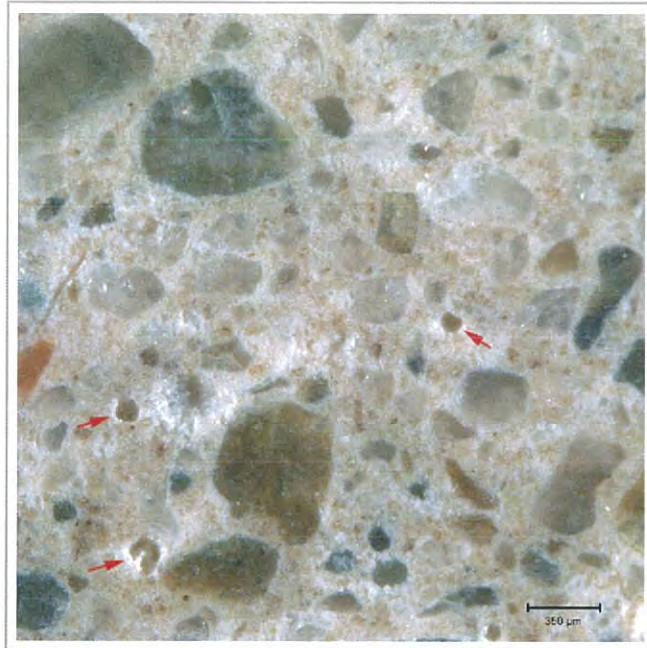


Figure C5. Oblique reflected light photomicrograph of polished surface showing voids (red arrows).



Figure C6. Photograph of the polished surface showing coarse aggregate; scale in millimeters.

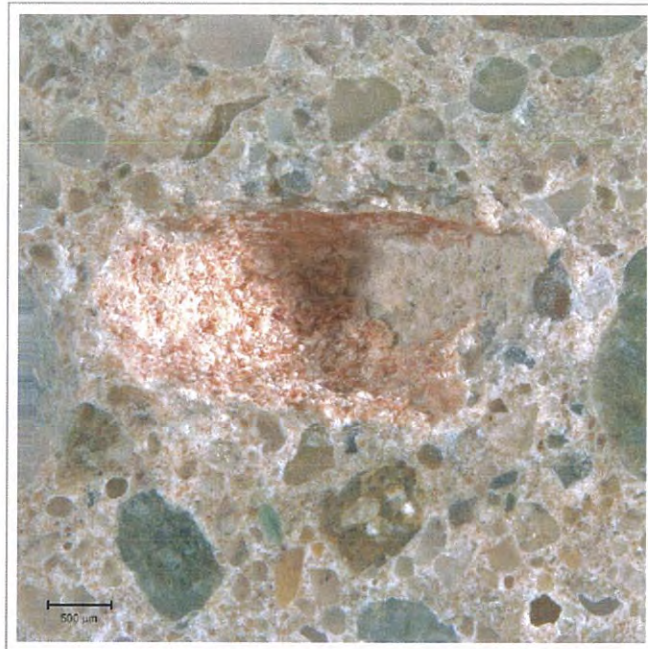


Figure C7. Reflected light photomicrograph of polished surface showing rust-colored sand on an aggregate socket.

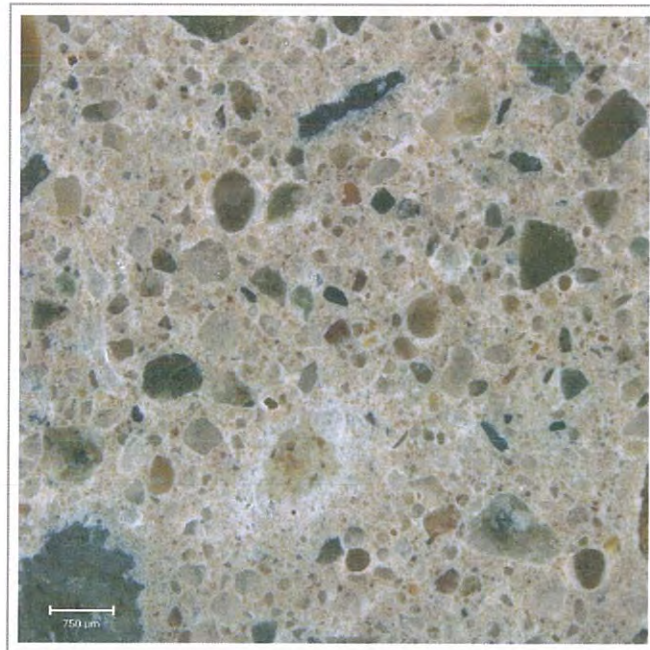


Figure C8. Reflected light photomicrograph of polished surface showing the fine aggregate.

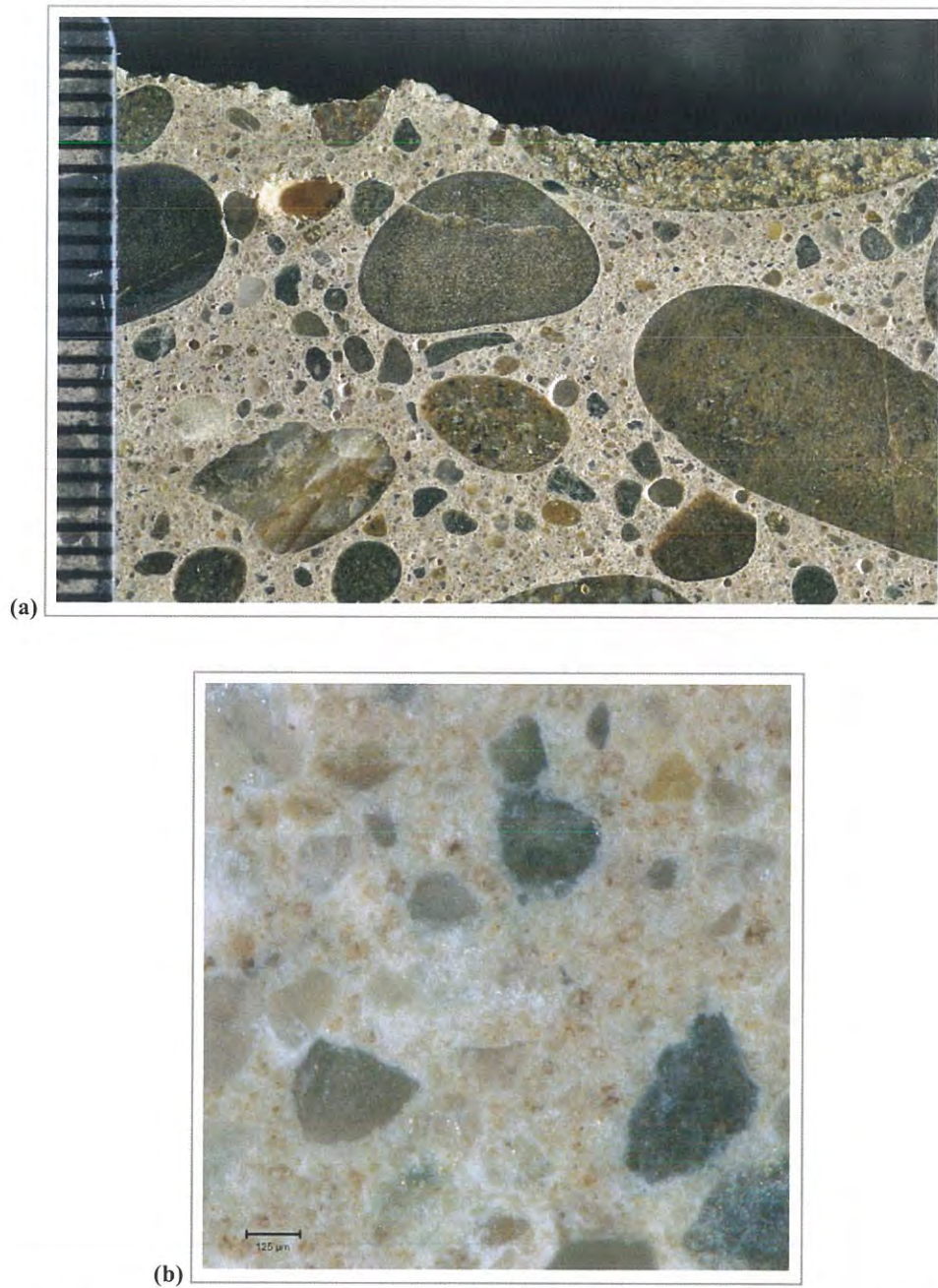


Figure C9. (a) Photograph of polished surface showing overview of paste at the top of the core. The scale is in millimeters. (b) Reflected light photomicrograph of polished surface showing detail of paste texture and luster in the middle of the petrography section of the core.

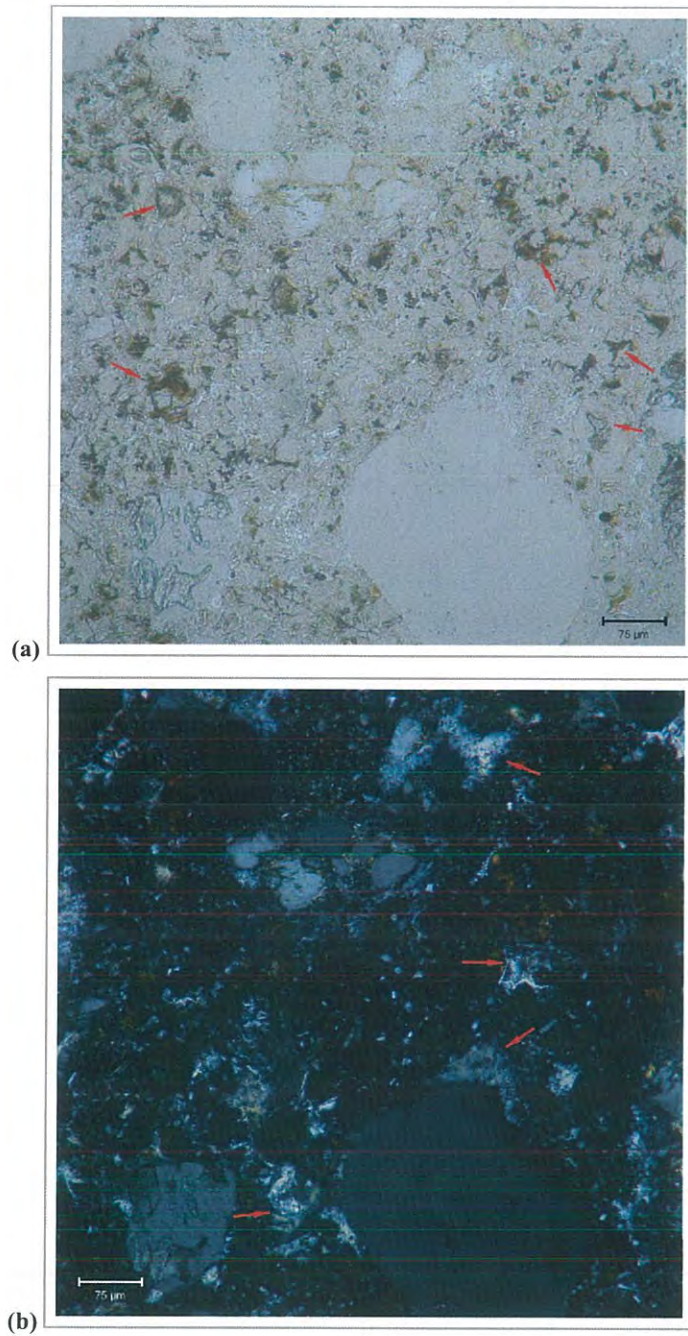


Figure C10. Transmitted light photomicrographs of thin section from the concrete core showing detail of paste in (a) plane-polarized and (b) cross-polarized light. The red arrows in (a) indicate RRCG; in (b) they indicate CH.

APPENDIX C: CTV Building Collapse Core Petrography
Sample ID: Core C4B (16YD5333)

Report No. DRP12.960
Date: 8 May 2012

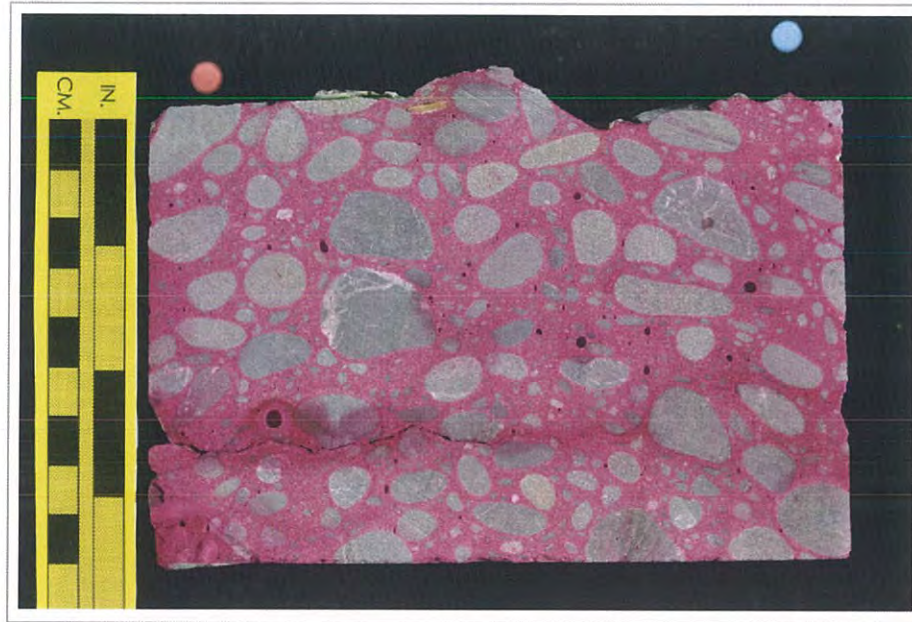


Figure C11. Photograph showing phenolphthalein stained surface.

APPENDIX D: CTV Building Collapse Core Petrography
 Sample ID: Core C4T 1/2 (16YD5359)

Report No. DRP12.960
 Date: 8 May 2012

1. RECEIVED CONDITION	
ORIENTATION	Vertical core taken through center of recovered column measures 145 mm (5 3/4 in.) in diameter and 125 mm (~ 5 in.) in length (Figure D1, D2). The entire core was used for petrography.
SURFACES	The top and bottom surfaces are fractures such that the core represents a partial thickness of the column. Portions of the top surface show saw cuts.
GENERAL CONDITION	The concrete is hard and compact and rings lightly when sounded with a hammer. The as-received fracture surface at the bottom of the core cuts around aggregate particles (Figure D3).

2. EMBEDDED OBJECTS	
GENERAL	None observed.

3. CRACKING	
MACROSCOPIC	None observed.
MICROSCOPIC	No significant microcracking observed. Rare, randomly oriented microcracks measuring less than 10 µm (2.5 mil) and 1 mm (40 mil) long observed (Figure D4)

4. VOIDS	
VOID SYSTEM	Concrete is not air-entrained and contains less than 3% air by visual estimation (not determined following ASTM C457; Figure D5). The consolidation of the concrete is good with no large entrapped voids or bleed voids observed.
VOID FILLINGS	Void are mostly free of secondary deposits; rare to occasional voids contain deposits of ettringite.

5. COARSE AGGREGATE	
PHYSICAL PROPERTIES	Natural river gravel with 19 mm (3/4 in.) nominal top size (Figure D6). The rocks are hard and competent. The particles are mostly oblong in shape with well-rounded to round edges but sub-equant, rounded particles are also make up a significant portion of the aggregate. No alignment of elongated particles observed. The grading and distribution is fairly even.
ROCK TYPES	The aggregate is siliceous in composition and consists primarily of metagraywackes with minor amounts of granitic rocks. Other components include quartzites and more mafic igneous rocks such as granodiorite and diorite. The metagraywackes range from very fine-grained rocks to rocks that have fine grained matrices and angular to sub-angular particles of feldspar, quartz, and biotite. The quartzites are commonly medium-grained and range in composition from arenitic to arkosic. Many of these components are potentially susceptible to alkali-silica reaction (ASR).
OTHER FEATURES	No deleterious coatings or incrustations observed. No low w/c mortar coatings observed. No reaction rims, significant internal microcracking, deposits of gel or other evidence of ASR observed. Minor weathering rims observed on occasional particles.

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 Sample ID: Core C4T 1/2 (16YD5359)

Report No. DRP12.960
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6. FINE AGGREGATE

PHYSICAL PROPERTIES	Natural river sand consists of rocks that are hard and competent (Figure D7). The particles are sub-equant to oblong in shape with sub-rounded to sub-angular edges. The grading and distribution are relatively even.
ROCK TYPES	The sand is mostly siliceous in composition and consists of rocks similar to those observed in the coarse aggregate, suggesting they are derived from a common geological source. The finer sieve sizes contain particles of quartz, feldspar, biotite and metallic oxide minerals.
OTHER FEATURES	No deleterious coatings or incrustations observed and no low w/c mortar coatings observed. No evidence of ASR observed.

7. PASTE OBSERVATIONS

POLISHED SURFACE	Paste is light brownish gray (Munsell 10YR/6/2) when viewed macroscopically but is mottled from white to light brown when viewed at high magnification under reflected light (Figure D8). The paste has a smooth texture and a sub-vitreous luster and is moderately hard (Mohs ~ 3.5).
THIN SECTION*	The paste contains hydrated portland cement; no fly ash, slag cement or other SCM were observed (Figure D9). The hydration is normal with 3-6% RRCG that consist mostly of belite and interstitial aluminate and ferrite. CH makes up 15-25% of the paste, is fine to medium-grained and the distribution is somewhat uneven.
FRESH FRACTURE SURFACE	Fracture surface is light gray, has a granular texture and a dull luster. The fracture cuts through ~ 20% of the aggregate particles.
* Abbreviations as follows: RRCG = relict and residual cement grains; SCM = supplemental cementitious materials; CH = calcium hydroxide; ITZ = interfacial transition zone. Modal abundances are based on visual estimations.	

8. SECONDARY DEPOSITS

PHENOLPHTHALEIN	Entire surface stains purple (Figure D10).
DEPOSITS	Deposits of ettringite observed in rare voids. No carbonation observed.

FIGURES



Figure D1. Photographs showing (a) oblique view of the top and side of the core with identification labels and (b) the top of the core. The red and blue dots show the orientation of the saw cuts used to prepare the sample.



Figure D1 (cont'd). (c) Photograph showing the bottom of the core.



Figure D2. Photograph showing the polished surface of the core.



Figure D3. Photograph showing detail of the top fracture surface of the core; scale in millimeters.

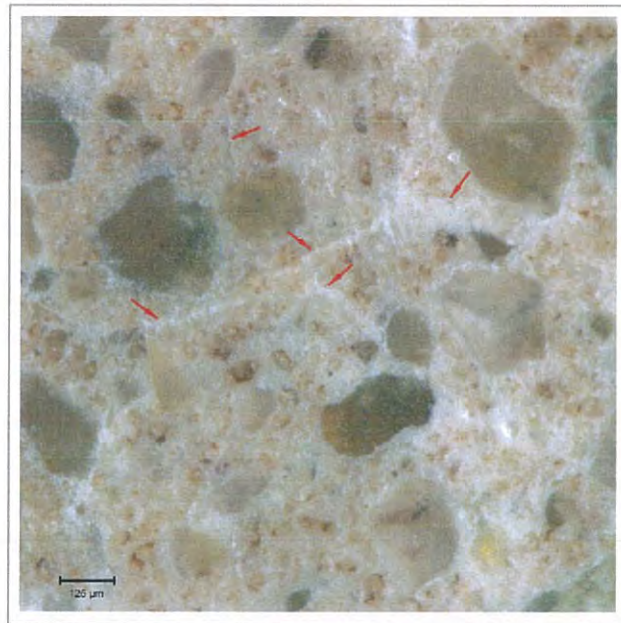


Figure D4. Reflected light photomicrograph of polished surface showing detail of microcrack (red arrows).

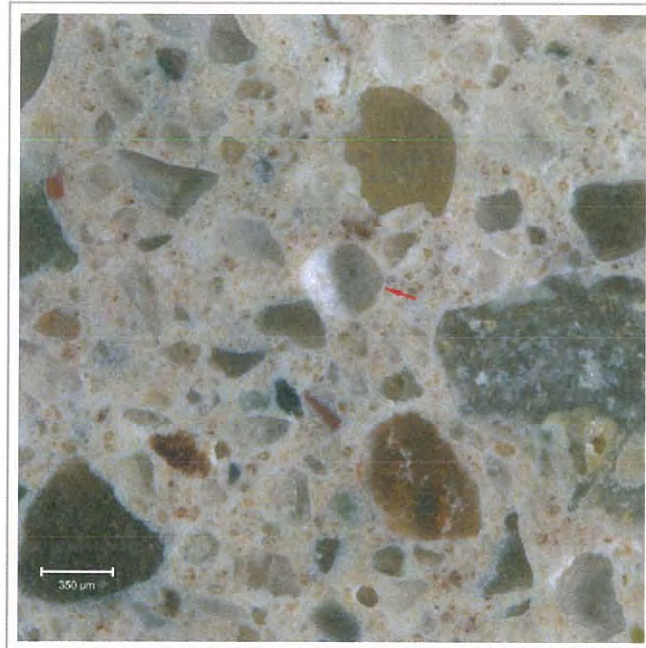


Figure D5. Oblique reflected light photomicrograph of polished surface showing view of voids (red arrow and dark circles).



Figure D6 (cont'd). Photograph of the polished surface showing coarse aggregate; scale in millimeters.

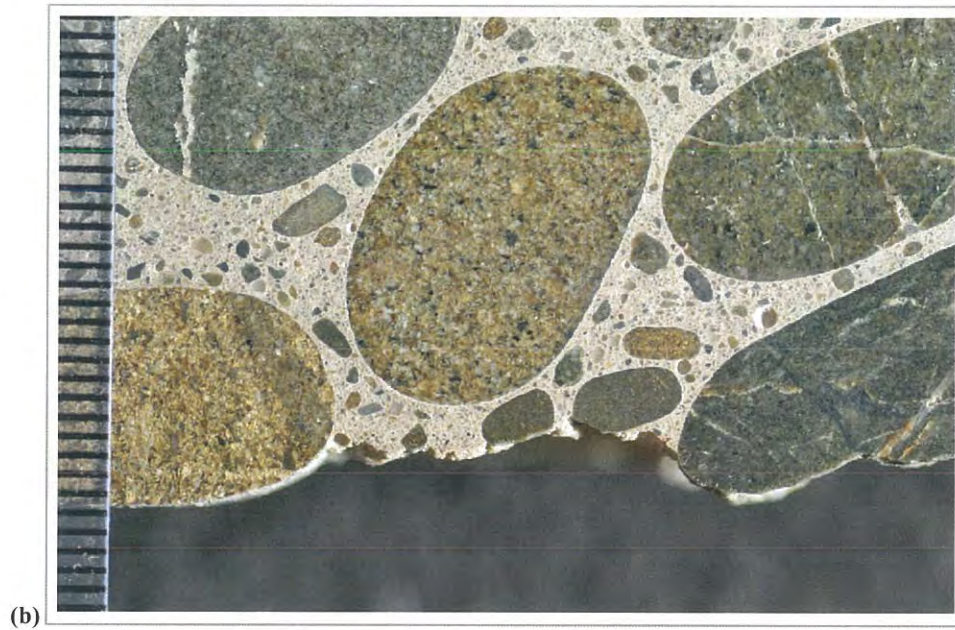


Figure D6 (cont'd). Photograph of the polished surface showing coarse aggregate near bottom fracture surface; scale in millimeters.

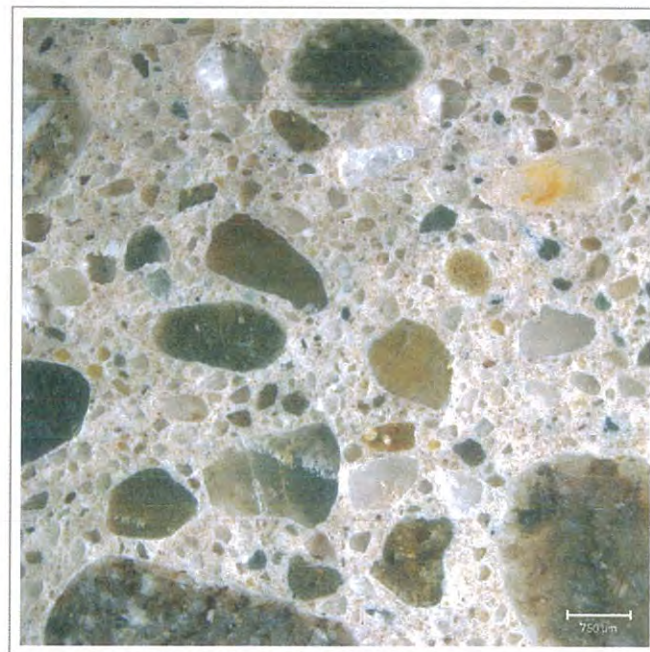


Figure D7. Reflected light photomicrograph of polished surface showing the fine aggregate.

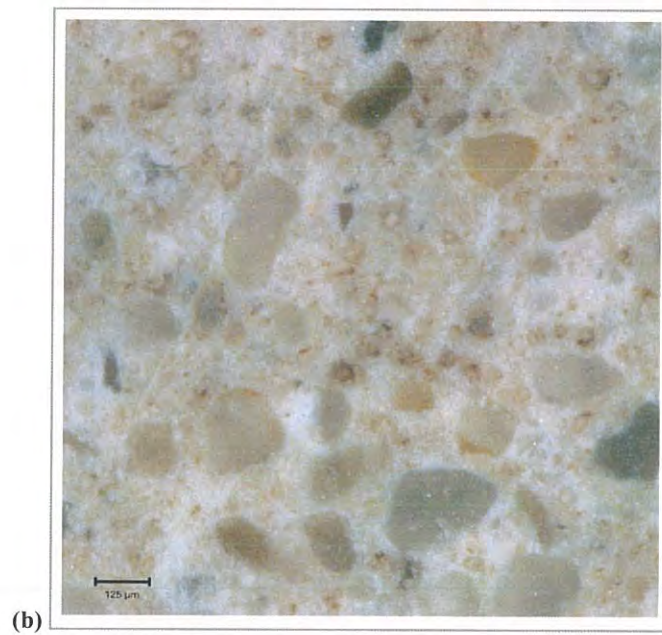


Figure D8. (a) Photograph of polished surface showing overview of paste at the top of the core. The scale is in millimeters. (b) Reflected light photomicrograph of polished surface showing detail of paste texture and luster in the middle of the core.

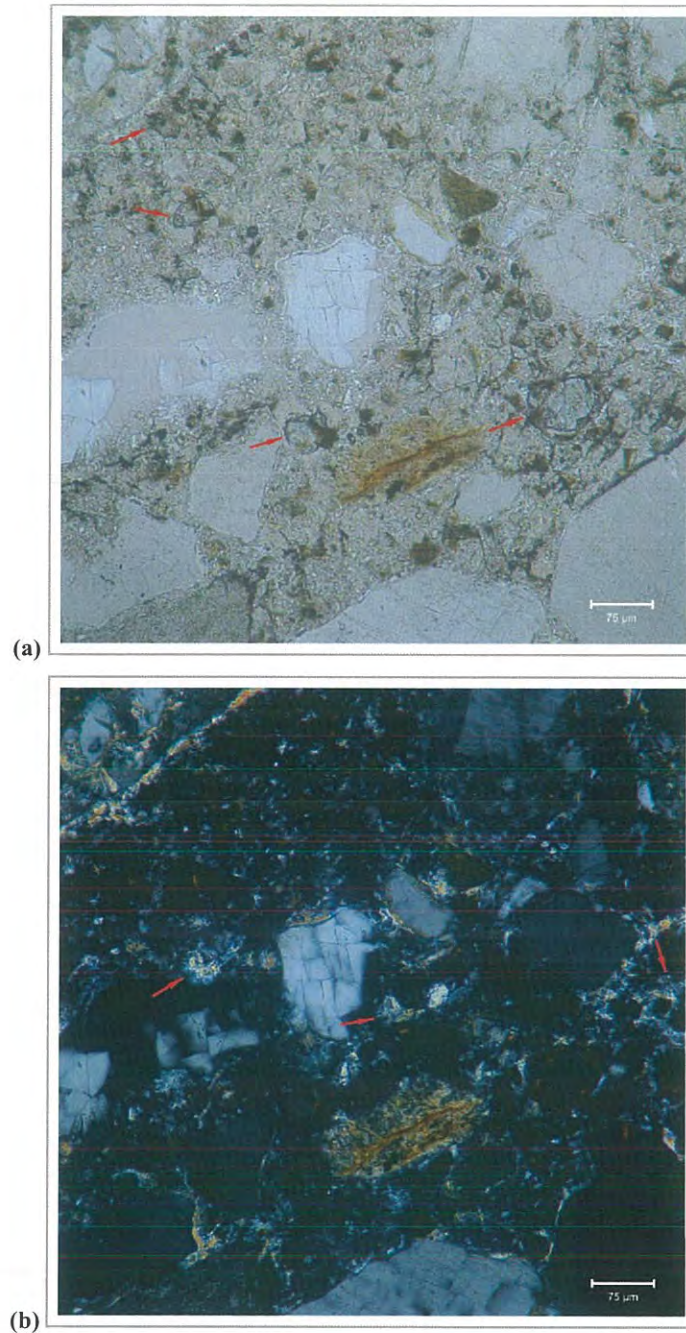


Figure D9. Transmitted light photomicrographs of thin section from the concrete core showing detail of paste in (a) plane-polarized and (b) cross-polarized light. The red arrows in (a) indicate RRCG; in (b) they indicate CH.

APPENDIX D: CTV Building Collapse Core Petrography
Sample ID: Core C4T 1/2 (16YD5359)

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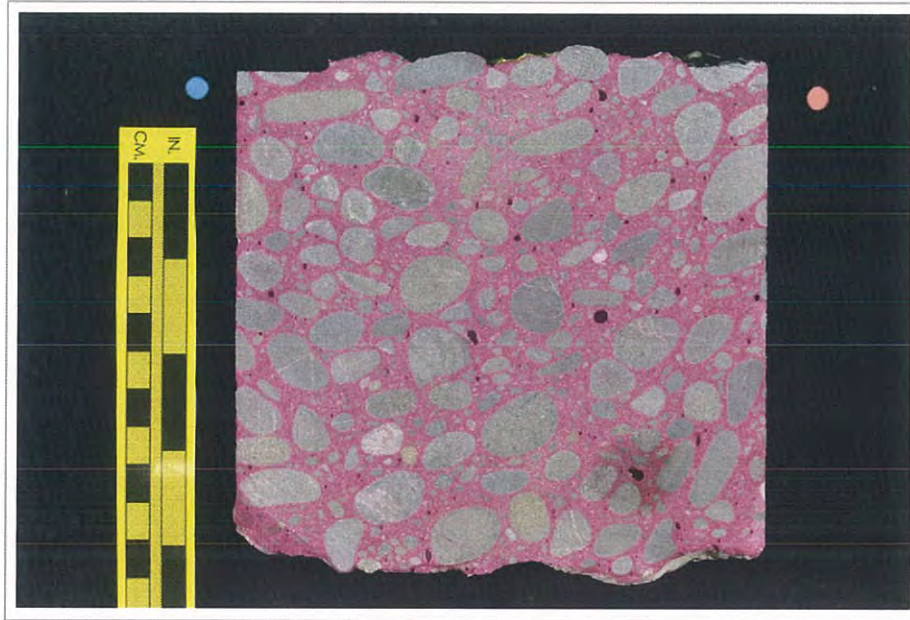


Figure D10. Photographs showing (a) overview of phenolphthalein stained surface and (b) detail of surface near the top of the core. Scale in millimeters in (b).

APPENDIX E: CTV Building Collapse Core Petrography
 Sample ID: Core C7T 1/2 (I6YD5360)

Report No. DRP12.960
 Date: 9 May 2012

1. RECEIVED CONDITION	
ORIENTATION	Vertical core taken through center of recovered column measures 145 mm (5 3/4 in.) in diameter and 300 mm (12 in.) in length (Figure E1). The middle section of the core was trimmed and tested for physical properties such as compressive strength and the bottom section was used for petrography. Both sides of the slab cut from this section were polished (Figure E2).
SURFACES	The top and bottom surfaces are saw cut (with multiple passes evident) such that the core represents a partial thickness of the column.
GENERAL CONDITION	The concrete is hard and compact and rings lightly when sounded with a hammer.

2. EMBEDDED OBJECTS	
GENERAL	None observed.

3. CRACKING	
MACROSCOPIC	None observed.
MICROSCOPIC	No significant microcracking observed.

4. VOIDS	
VOID SYSTEM	Concrete is not air-entrained and contains 1.0% air by ASTM C457 (Figure E3). The consolidation of the concrete is good with no large entrapped voids or bleed voids observed.
VOID FILLINGS	Voids are mostly free of secondary deposits; rare to occasional voids show minor deposits of ettringite, primarily as isolated rosettes.

5. COARSE AGGREGATE	
PHYSICAL PROPERTIES	Natural river gravel with 19 mm (3/4 in.) nominal top size (Figure E4). The rocks are hard and competent. The particles are mostly oblong in shape with well-rounded to round edges but sub-equant, rounded particles are also make up a significant portion of the aggregate. The grading and distribution are even. No significant alignment of elongated particles was observed.
ROCK TYPES	The aggregate is siliceous in composition and consists primarily of metagraywackes with minor amounts of granitic rocks. Other components include quartzites and more mafic igneous rocks such as granodiorite and diorite. The metagraywackes are distinguished by very fine grained matrices and angular to sub-angular particles of feldspar and quartz. The quartzites are commonly medium-grained and range in composition from arenitic to arkosic. Many of these components are potentially susceptible to alkali-silica reaction (ASR).
OTHER FEATURES	No deleterious coatings or incrustations observed. No low w/c mortar coatings observed. No reaction rims, significant internal microcracking, deposits of gel or other evidence of ASR observed. Peripheral microcracking observed in some particles; these terminate at the boundary with the paste (Figure E5). Minor loss of paste observed around some aggregate particles (Figure E6).

APPENDIX E: CTV Building Collapse Core Petrography
 Sample ID: Core C7T 1/2 (I6YD5360)

Report No. DRP12.960
 Date: 9 May 2012

6. FINE AGGREGATE

PHYSICAL PROPERTIES	Natural river sand consists of rocks that are hard and competent (Figure E7). The particles are sub-equant to oblong in shape with sub-rounded to sub-angular edges. The grading and distribution are relatively even.
ROCK TYPES	The sand is mostly siliceous in composition and consists of rocks similar to those observed in the coarse aggregate, suggesting they are derived from a common geological source. The finer sieve sizes contain particles of quartz, feldspar, biotite and metallic oxide minerals.
OTHER FEATURES	No deleterious coatings or incrustations observed and no low w/c mortar coatings observed. No evidence of ASR observed.

7. PASTE OBSERVATIONS

POLISHED SURFACE	Paste is light gray (Munsell 10YR/7/2) when viewed macroscopically but is mottled from white to light brown when viewed at high magnification under reflected light (Figure E8). The paste has a granular to smooth texture and a sub-vitreous luster and is moderately soft (Mohs ~ 3).
THIN SECTION*	The paste contains hydrated portland cement; no fly ash, slag cement or other SCM were observed (Figure E9). The hydration is advanced with less than 3% RRCG that consist mostly of belite and interstitial aluminate and ferrite. CH makes up 15-25% of the paste, is coarse-grained and unevenly distributed.
FRESH FRACTURE SURFACE	Fracture surface is light gray to pale brown, has a granular to punky texture and a dull to chalky luster. The surface cuts through ~ 20% of the aggregate.
* Abbreviations as follows: RRCG = relict and residual cement grains; SCM = supplemental cementitious materials; CH = calcium hydroxide; ITZ = interfacial transition zone. Modal abundances are based on visual estimations.	

8. SECONDARY DEPOSITS

PHENOLPHTHALEIN	Entire surface stains purple (Figure E10).
DEPOSITS	Deposits of ettringite observed in occasional voids. No carbonation observed.

FIGURES

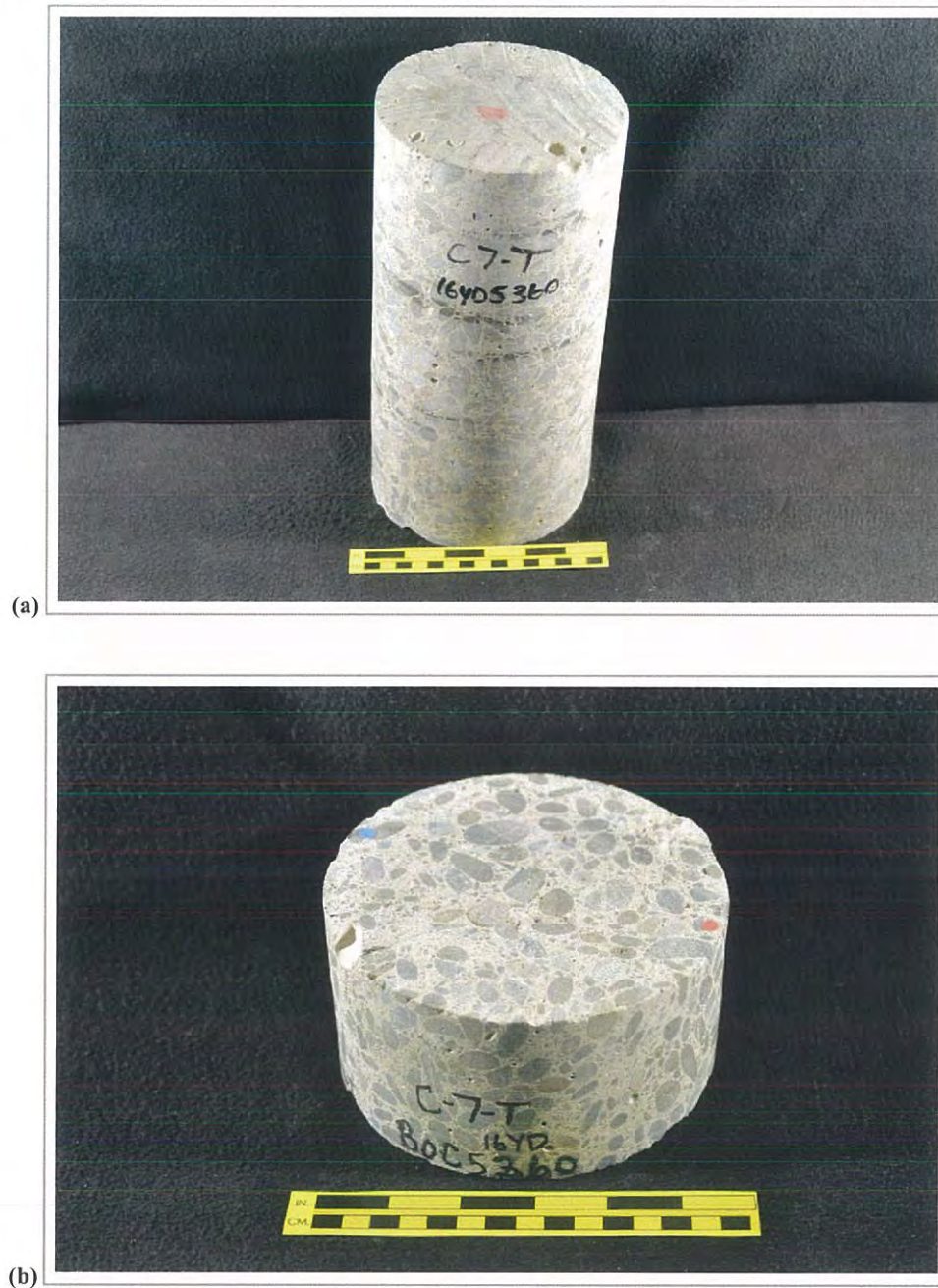


Figure E1. Photographs showing oblique views (a) of the top and side of the core with identification labels in the as-received condition and (b) the lower section of the core used for petrography after the core was trimmed for strength testing. The red and blue dots in (b) show the orientation of the saw cuts used to prepare the sample for petrography.

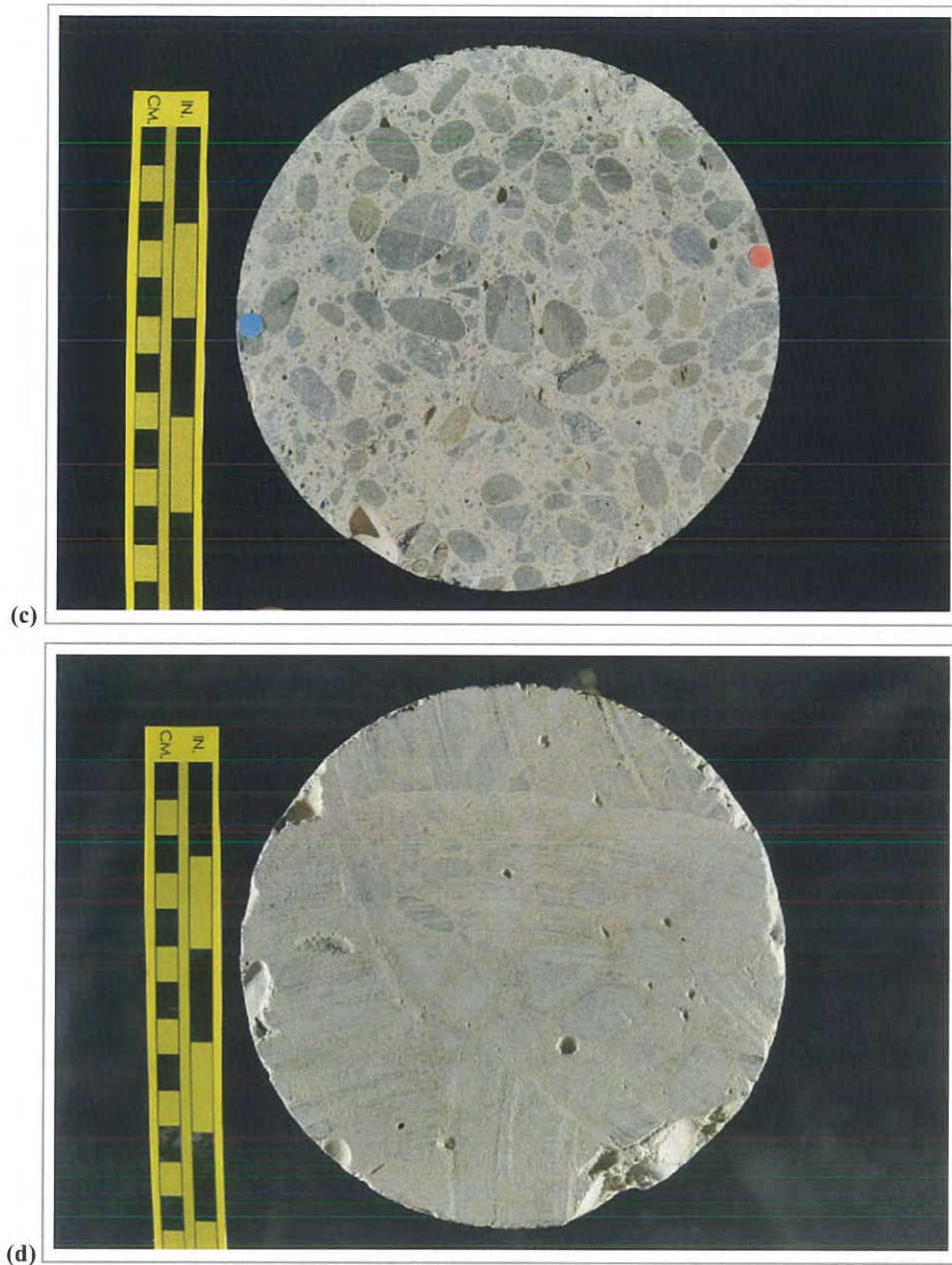


Figure E1 (cont'd). Photographs showing the (a) top and (b) bottom surfaces of the section of the core used for petrography. The red and blue dots in (a) show the orientation of the saw cuts used to prepare the polished surface of the sample.

APPENDIX E: CTV Building Collapse Core Petrography
Sample ID: Core C7T 1/2 (16YD5360)

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Figure E2. Photograph showing one of the polished surfaces of the core.

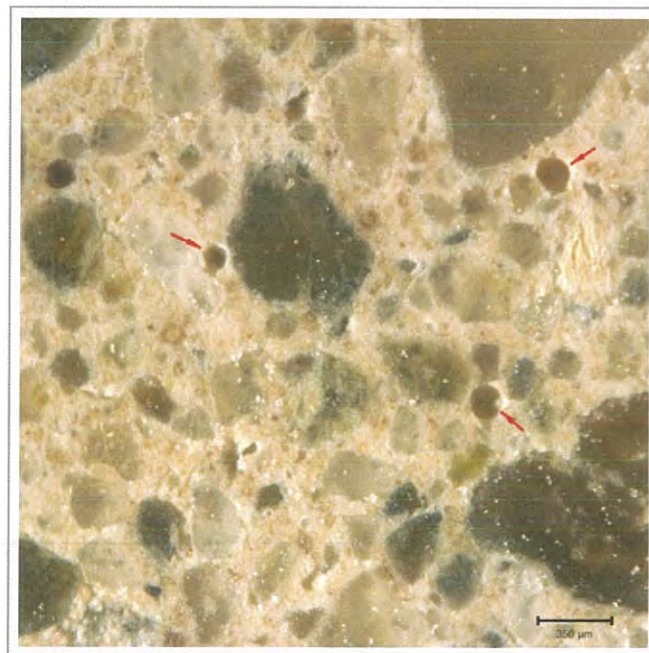


Figure E3. Oblique reflected light photomicrograph of polished surface showing voids (red arrows).



Figure E4. Photograph of the polished surface showing coarse aggregate; scale in millimeters.

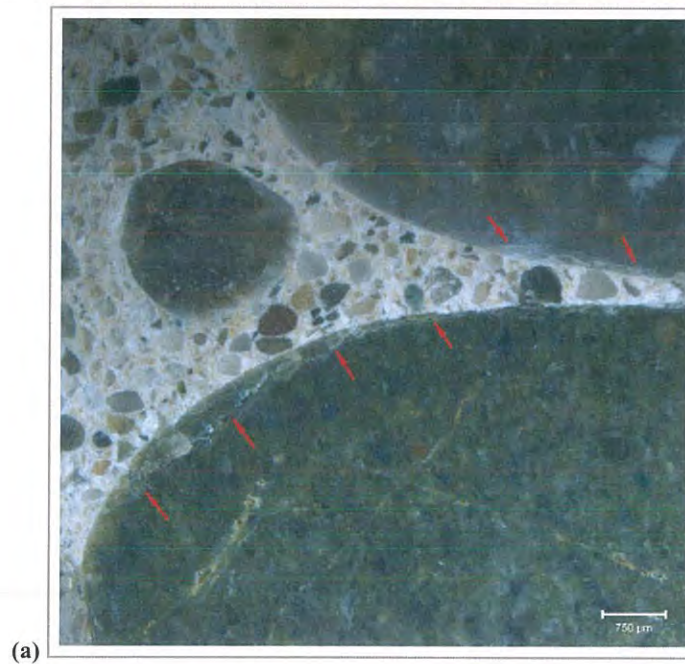


Figure E5. Reflected light photomicrograph of polished surface showing peripheral microcracks (red arrows) in aggregate particles. Note the microcracks do not cut into the paste.

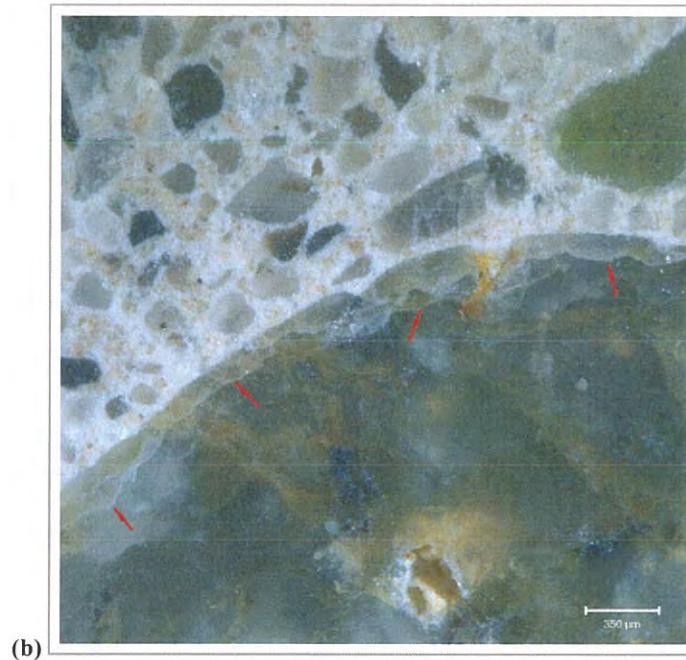


Figure E5 (cont'd). (b) Reflected light photomicrograph of polished surface showing detail of peripheral microcracking (red arrows) in aggregate particle. Note the microcracks do not cut into the paste.

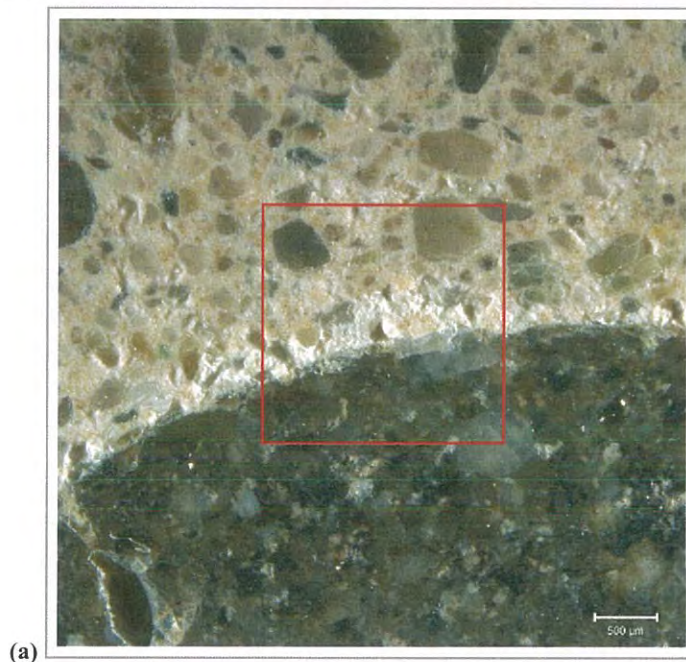


Figure E6. Reflected light photomicrograph of polished surface showing paste-aggregate contact where some loss of paste was observed. The red square indicates the approximate area of (b).

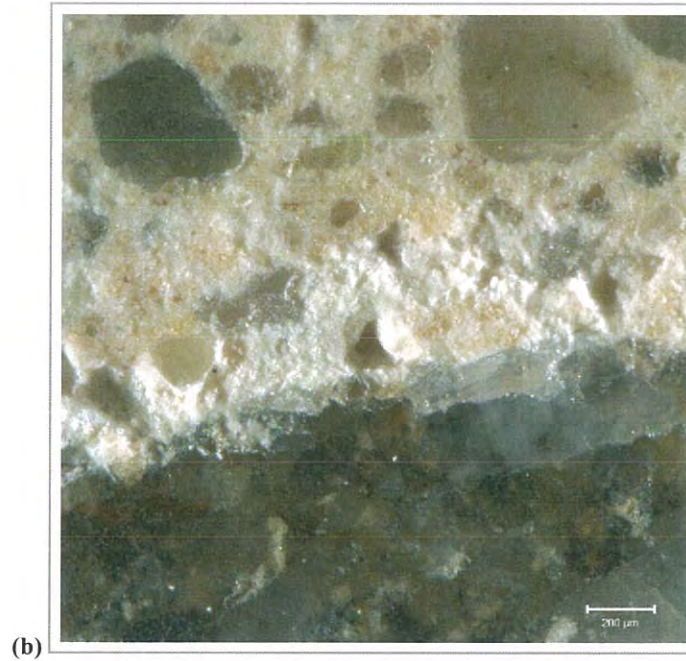


Figure E6. Reflected light photomicrograph of polished surface showing detail of paste-aggregate contact where some loss of paste was observed.

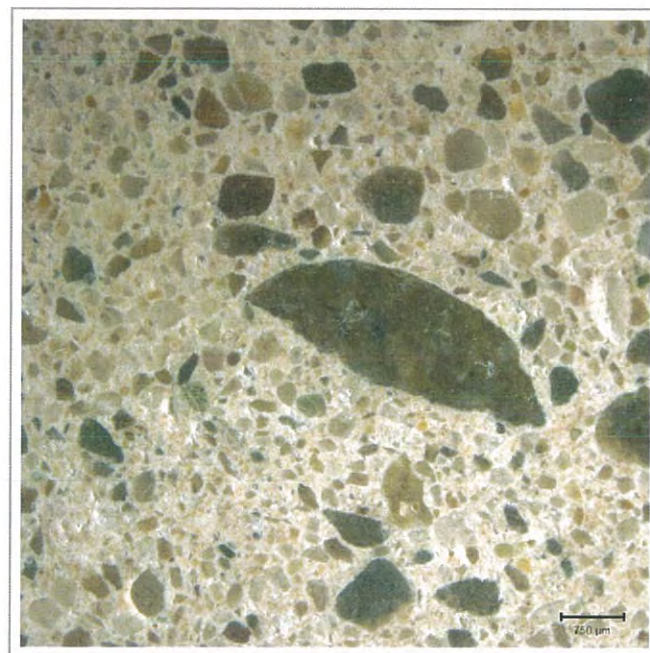


Figure E7. Reflected light photomicrograph of polished surface showing the fine aggregate.

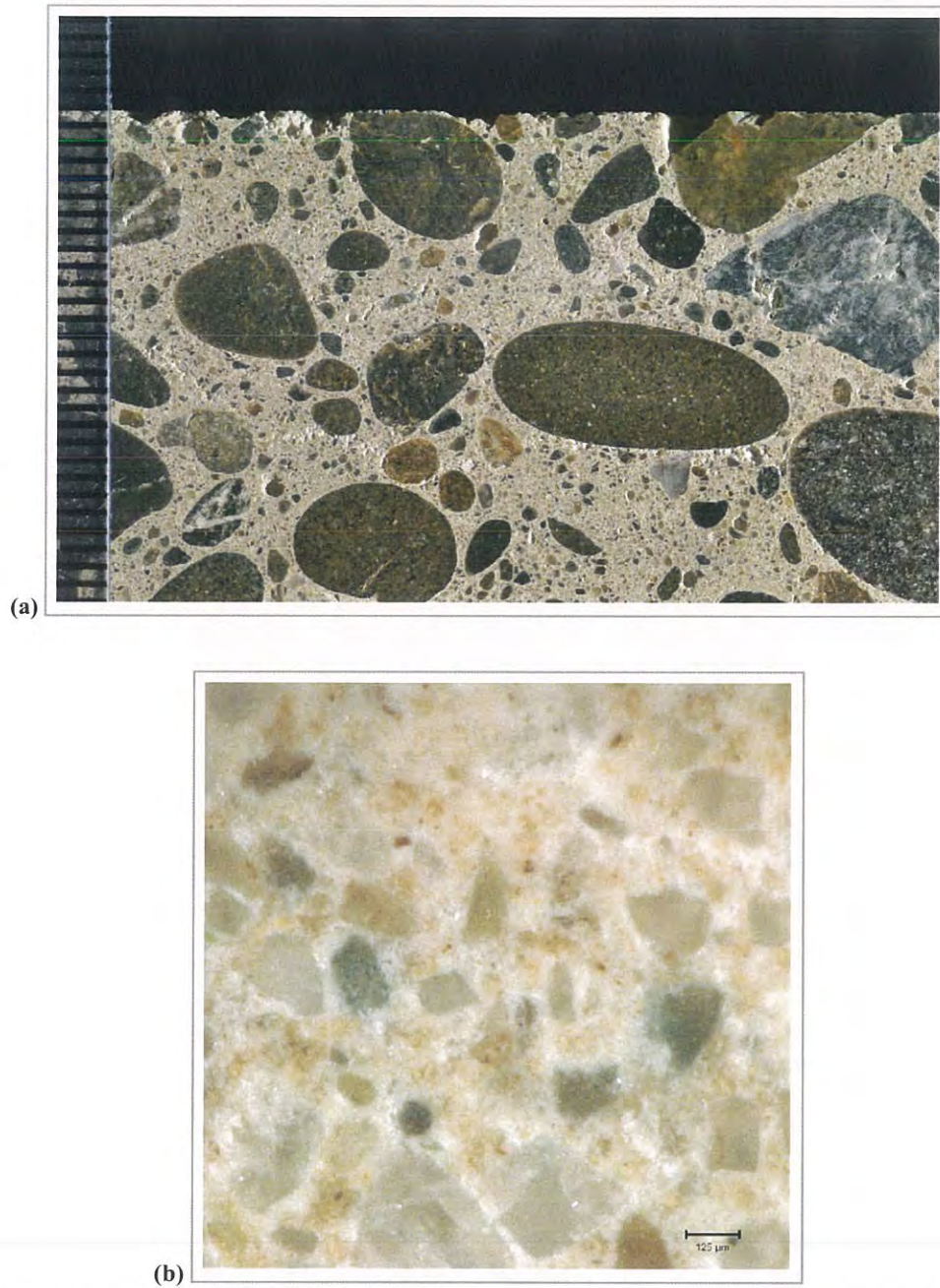


Figure E8. (a) Photograph of polished surface showing overview of paste at the top of the core. The scale is in millimeters. (b) Reflected light photomicrograph of polished surface showing detail of paste texture and luster in the middle of the petrography section of the core.

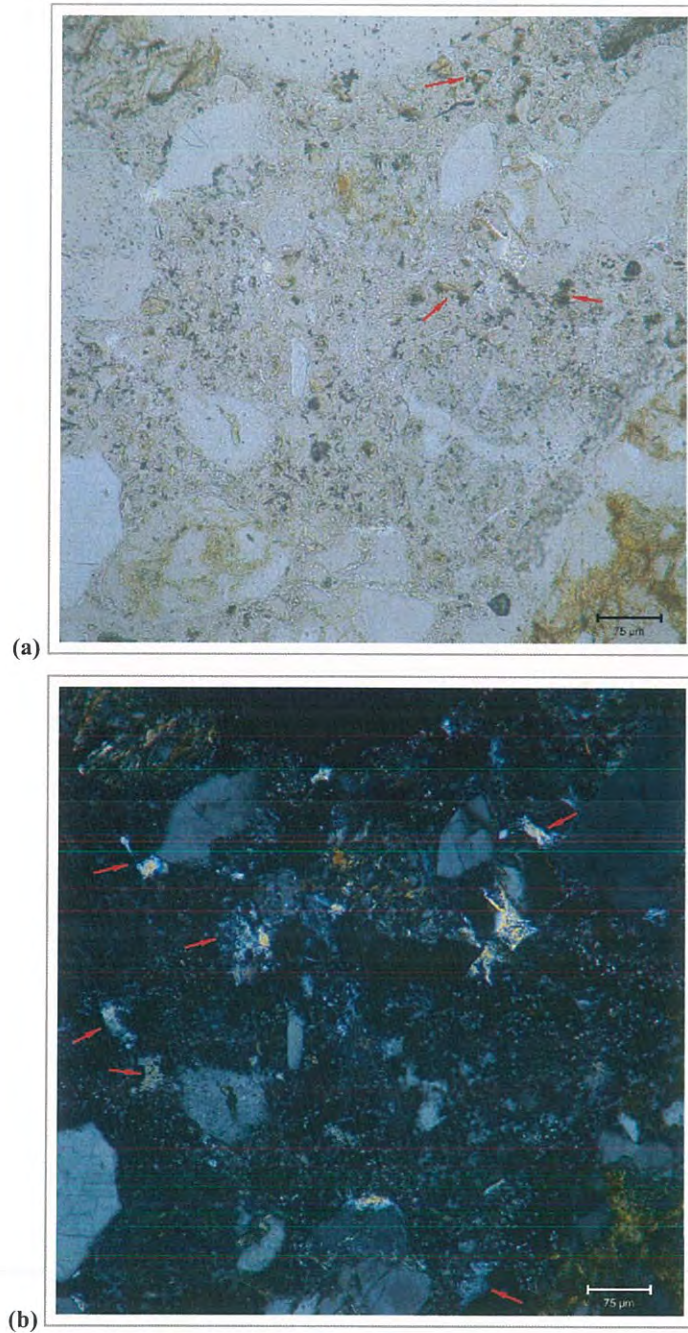


Figure E9. Transmitted light photomicrographs of thin section from the concrete core showing detail of paste in (a) plane-polarized and (b) cross-polarized light. The red arrows in (a) indicate RRCG; in (b) they indicate CH.

APPENDIX E: CTV Building Collapse Core Petrography
Sample ID: Core C7T 1/2 (16YD5360)

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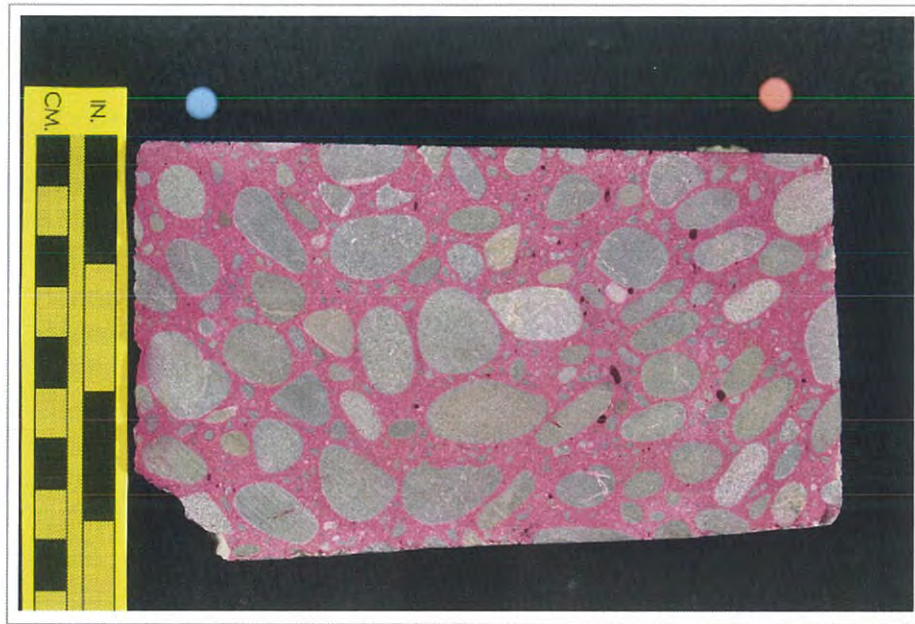


Figure E10. Photograph showing phenolphthalein stained surface.

APPENDIX F: CTV Building Collapse Core Petrography
 Sample ID: Core C12B 1/2 (16YD5361)

Report No. DRP12.960
 Date: 9 May 2012

1. RECEIVED CONDITION	
ORIENTATION	Vertical core taken through center of recovered column measures 145 mm (5 3/4 in.) in diameter and 110-155 mm (4 3/8-6 1/8 in.) in length (Figure F1). The top section of the core was trimmed and used for petrography and the bottom section was tested for physical properties such as compressive strength.
SURFACES	The top and bottom surfaces are fracture surfaces such that the core represents a partial thickness of the column. The fractures pass consistently around aggregate particles; the fracture surface at the top of the core is relatively clean whereas the lower surface was covered with a thin film of detritus or drilling mud (Figure F2). The piece used for petrography has a fracture surface at the top and a saw-cut at the bottom and is about 50 mm (2 in.) thick. Both sides of the slab cut from this section were polished (Figure F3).
GENERAL CONDITION	The concrete is hard and compact and rings lightly when sounded with a hammer.

2. EMBEDDED OBJECTS	
GENERAL	None observed.

3. CRACKING	
MACROSCOPIC	None observed.
MICROSCOPIC	A few microcracks were observed within the core. One microcrack is about 5 mm (200 mil) above the saw cut surface (45 mm or 1 3/4 in. from top surface; Figure F4). The microcrack strikes sub-vertically around and through aggregate particles for ~ 6 mm (1/4 in.) and ranges from 100-250 µm (4-10 mil) in width. Minor deposits of ettringite, similar to those observed in air voids, are present in the microcrack. The other microcrack is about 19 mm (3/4 in.) below the top surface and strikes sub-vertically for ~ 6 mm (1/4 in.) and is up to 250 µm (10 mil) wide (Figure F5). Minor deposits of ettringite, also similar to those observed in air voids, are present in the microcrack.

4. VOIDS	
VOID SYSTEM	Concrete is not air-entrained and contains 1.9% air by ASTM C457 (Figure F6). The consolidation of the concrete is good with no large entrapped voids or bleed voids observed.
VOID FILLINGS	Void commonly contain rosettes of ettringite.

APPENDIX F: CTV Building Collapse Core Petrography
 Sample ID: Core C12B 1/2 (16YD5361)

Report No. DRP12.960
 Date: 9 May 2012

5. COARSE AGGREGATE

PHYSICAL PROPERTIES	Natural river gravel with 19 mm (¾ in.) nominal top size (Figure F7). The rocks are hard and competent. The particles are mostly oblong in shape with well-rounded to round edges but sub-equant, rounded particles are also make up a significant portion of the aggregate. The grading and distribution are somewhat uneven. No significant alignment of elongated particles was observed.
ROCK TYPES	The aggregate is siliceous in composition and consists primarily of metagraywackes with minor amounts of granitic rocks. Other components include quartzites and more mafic igneous rocks such as granodiorite and diorite. The metagraywackes are distinguished by very fine grained matrices and angular to sub-angular particles of feldspar and quartz. The quartzites are commonly medium-grained and range in composition from arenitic to arkosic. Many of these components are potentially susceptible to alkali-silica reaction (ASR).
OTHER FEATURES	No deleterious coatings or incrustations observed. No low w/c mortar coatings observed. No reaction rims, significant internal microcracking, deposits of gel or other evidence of ASR observed.

6. FINE AGGREGATE

PHYSICAL PROPERTIES	Natural river sand consists of rocks that are hard and competent (Figure F8). The particles are sub-equant to oblong in shape with sub-rounded to sub-angular edges. The grading and distribution are relatively even.
ROCK TYPES	The sand is mostly siliceous in composition and consists of rocks similar to those observed in the coarse aggregate, suggesting they are derived from a common geological source. The finer sieve sizes contain particles of quartz, feldspar, biotite and metallic oxide minerals.
OTHER FEATURES	No deleterious coatings or incrustations observed and no low w/c mortar coatings observed. No evidence of ASR observed.

7. PASTE OBSERVATIONS

POLISHED SURFACE	Paste is light gray (Munsell 10YR/7/2) when observed macroscopically but is mottled from white to light brown when viewed at high magnification under reflected light (Figure F9). The paste has a granular to smooth texture and a sub-vitreous luster. The paste is moderately hard (Mohs ~ 3).
THIN SECTION*	The paste contains hydrated portland cement; no fly ash, slag cement or other SCM were observed (Figure F10). The hydration is advanced with less than 3% RRCG that consist mostly of belite and interstitial aluminate and ferrite. CH makes up 15-25% of the paste, is coarse-grained and unevenly distributed. Fine crystallites of calcium carbonate also observed intermittently.
FRESH FRACTURE SURFACE	Fracture surface is light gray to pale brown, has a granular to punky texture and a dull to chalky luster. The surface cuts through ~ 10% of the aggregate.

* Abbreviations as follows: RRCG = relict and residual cement grains; SCM = supplemental cementitious materials; CH = calcium hydroxide; ITZ = interfacial transition zone. Modal abundances are based on visual estimations.

8. SECONDARY DEPOSITS

PHENOLPHTHALEIN	Entire surface stains purple (Figure F11).
DEPOSITS	Deposits of ettringite commonly observed in voids and occasionally in microcracks. Very minor carbonation observed.

FIGURES

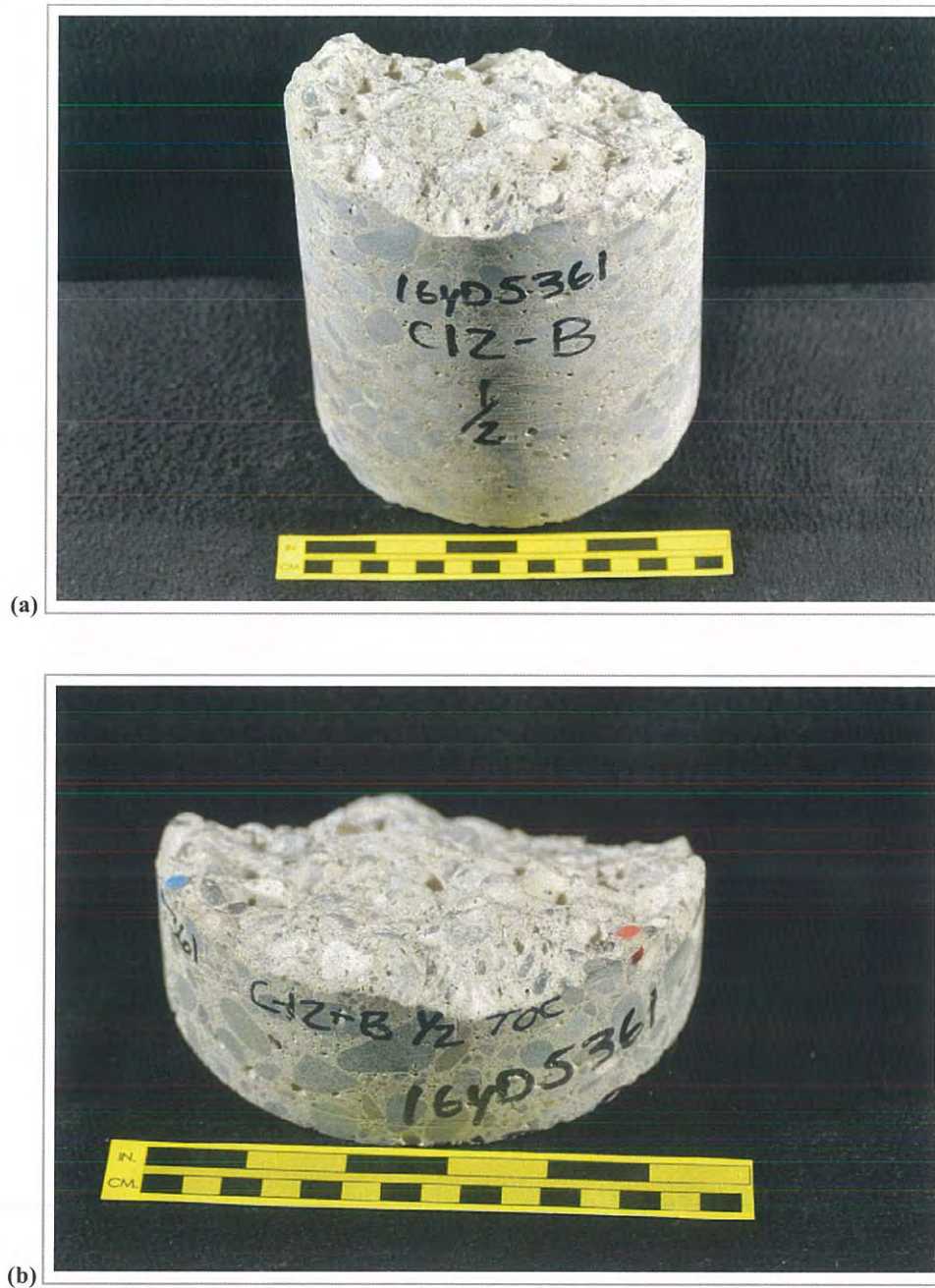


Figure F1. Photographs showing oblique views of the top and side of the core with identification labels (a) in as-received condition and (b) after the core was trimmed for testing. The red and blue dots in (b) show the orientation of the saw cuts used to prepare the sample.



Figure F1 (cont'd). Photographs showing the (a) top surface and (b) bottom surface of the core in as-received condition.



Figure F2. Photograph showing detail of the top surface of the core; scale in millimeters.



Figure F3. Photograph of one of the polished surfaces used for petrographic work.

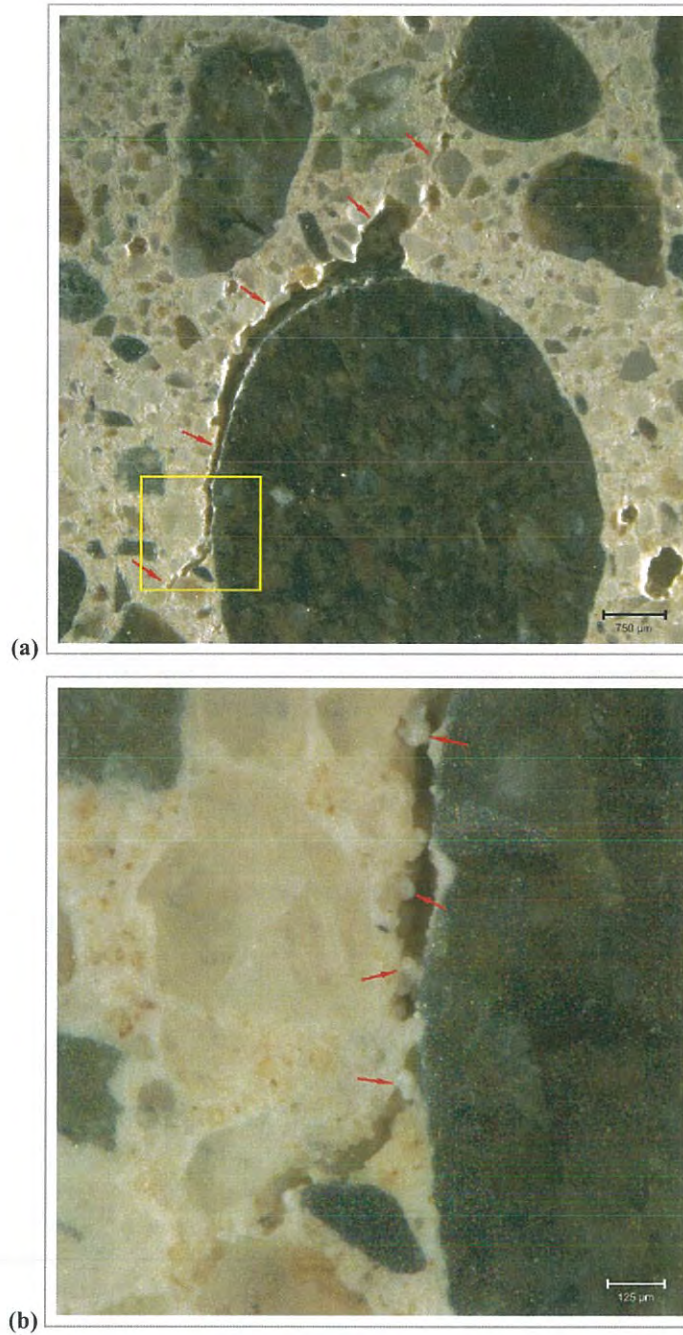


Figure F4. Reflected light photomicrographs of polished surface showing microcrack near the bottom of the polished surface. The red arrows in (a) indicate the microcrack and the yellow box shows the approximate area of (b), where the red arrows highlight rosettes of ettringite.

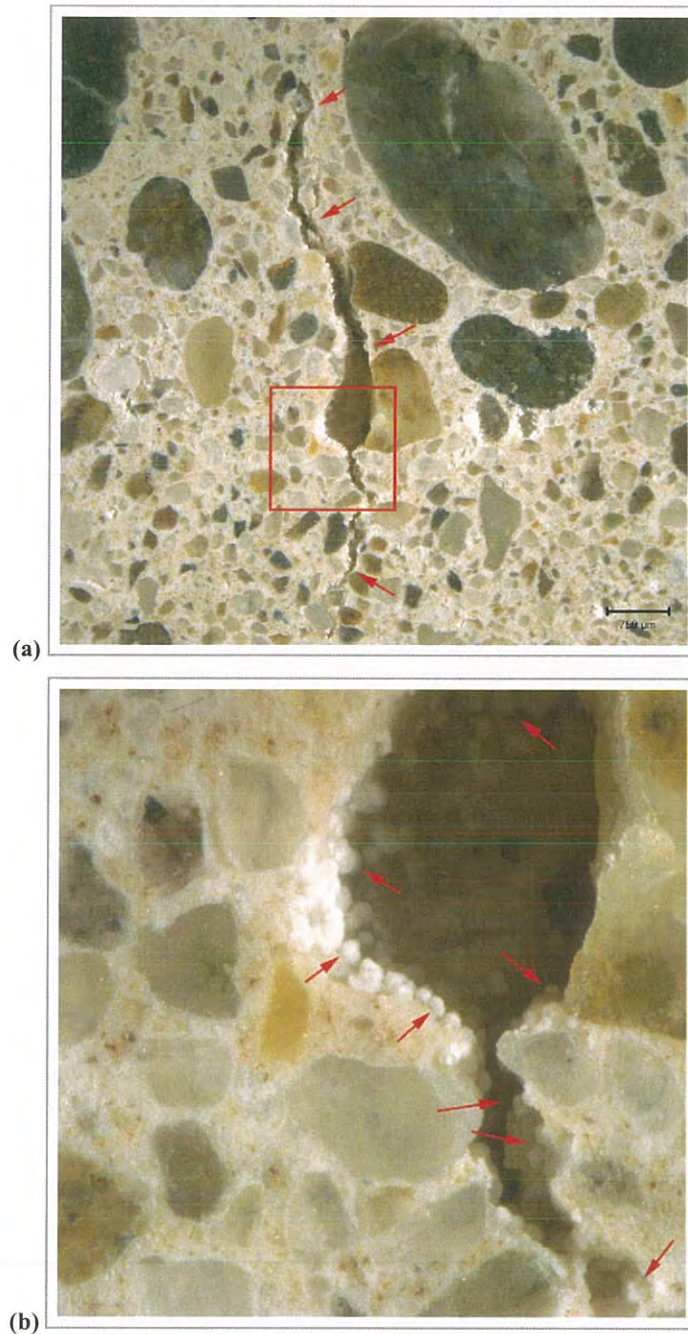


Figure F5. Reflected light photomicrographs of polished surface showing microcrack about 19 mm (¾ in.) from the top of the polished surface. The red arrows in (a) indicate the microcrack and the red box shows the approximate area of (b), where the red arrows highlight rosettes of ettringite.

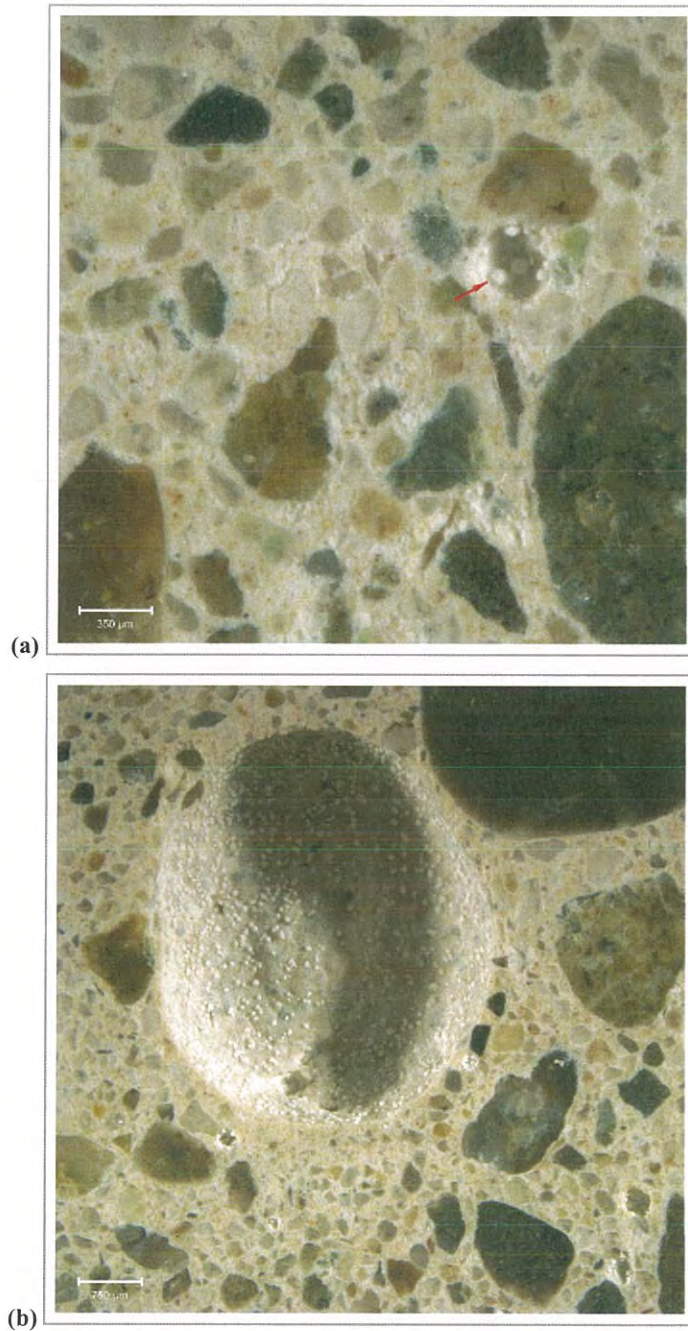


Figure F6. Oblique reflected light photomicrographs of polished surface showing view of voids. The red arrow in (a) highlights a rosette of ettringite in a relatively fine void. The white spots in the larger void shown in (b) are also rosettes of ettringite.



Figure F7. Photograph of the polished surface showing coarse aggregate; scale in millimeters.

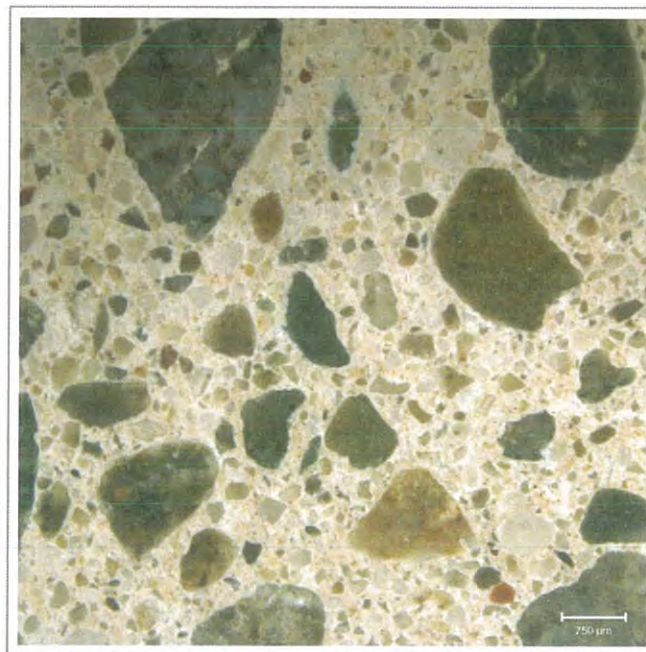


Figure F8. Reflected light photomicrograph of polished surface showing the fine aggregate.

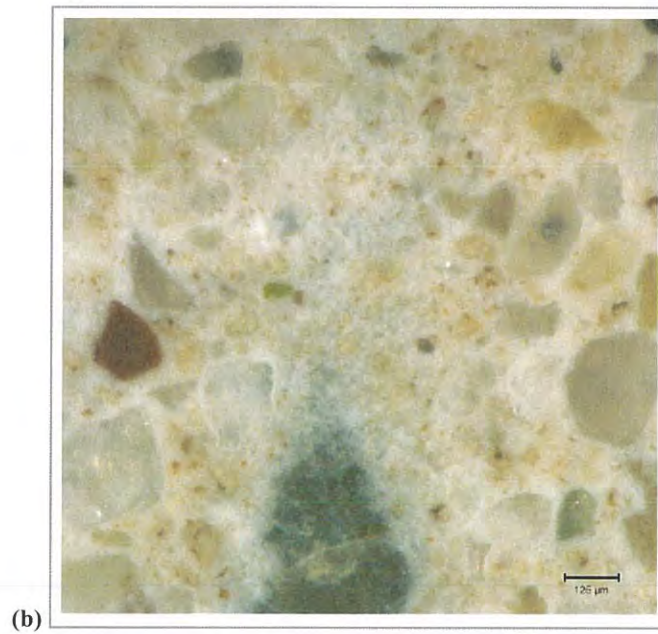


Figure F9. (a) Photograph of polished surface showing overview of paste at the top of the core. The scale is in millimeters. (b) Reflected light photomicrograph of polished surface showing detail of paste texture and luster.

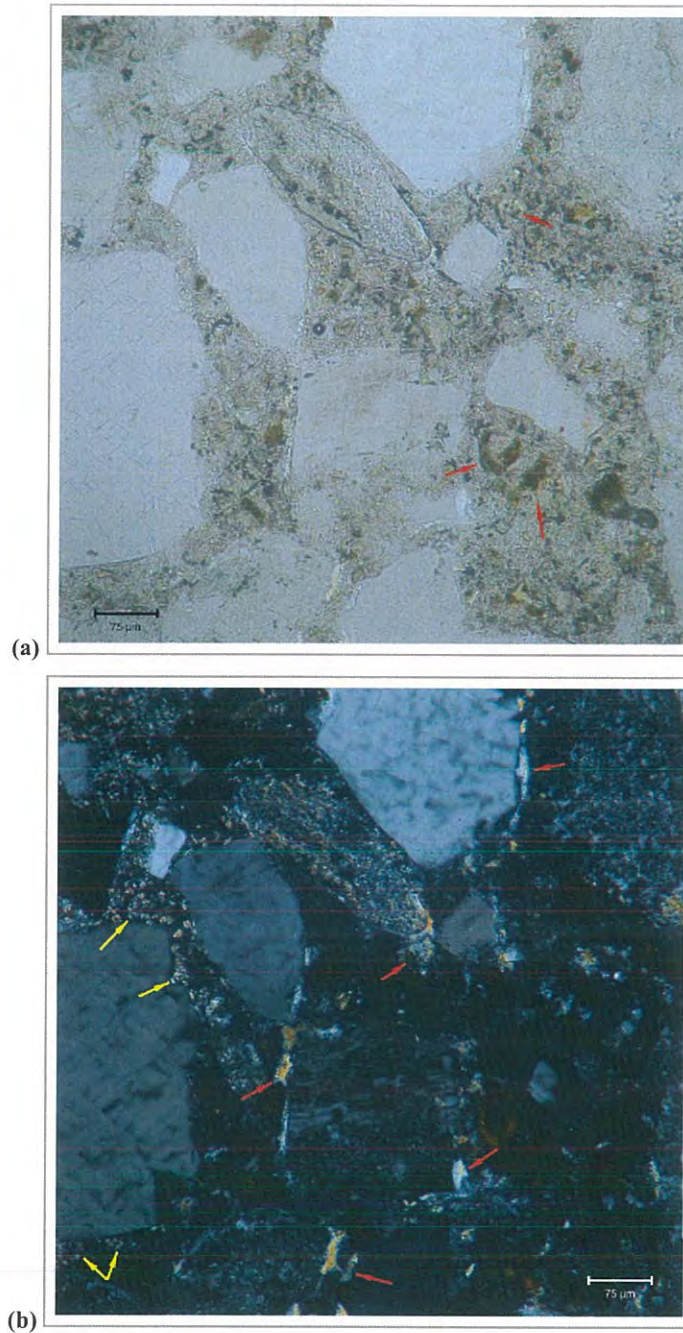


Figure F10. Transmitted light photomicrographs of thin section from the concrete core showing detail of paste in (a) plane-polarized and (b) cross-polarized light. The red arrows in (a) indicate RRCG; in (b) they indicate CH. The yellow arrows in (b) indicate crystallites of calcium carbonate.

APPENDIX F: CTV Building Collapse Core Petrography
Sample ID: Core C12B 1/2 (16YD5361)

Report No. DRP12.960
Date: 9 May 2012

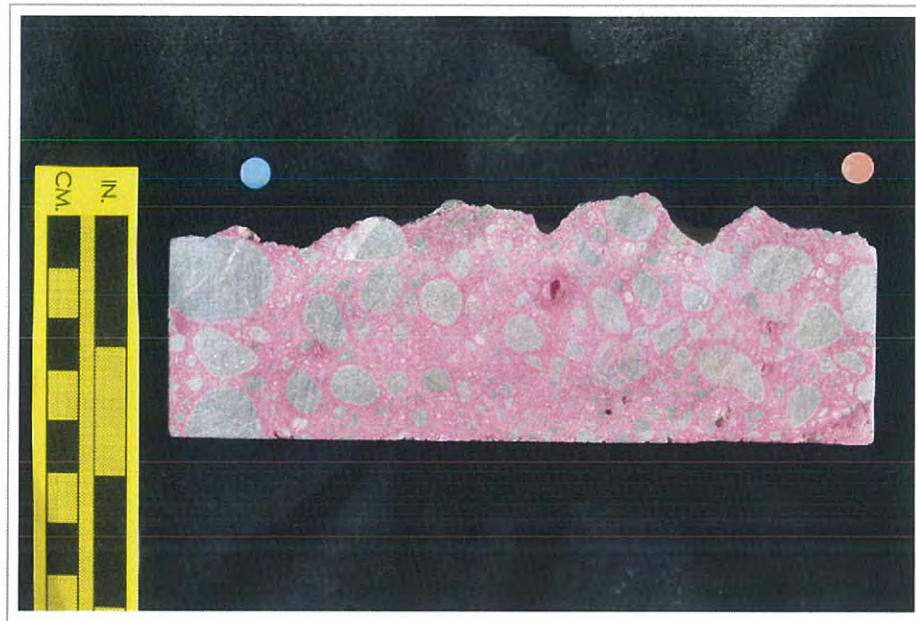


Figure F11. Photograph showing the phenolphthalein stained surface.

APPENDIX G: CTV Building Collapse Core Petrography
 Sample ID: Core R3 (16YD5362)

Report No. DRP12.960
 Date: 10 May 2012

1. RECEIVED CONDITION

ORIENTATION	Vertical core taken through center of recovered column measures 145 mm (5 ¾ in.) in diameter and 240-260 mm (9 ½ - 10 ¼ in.) in length (Figure G1). After trimming the core for strength testing the prepared surfaces (both sides of the slab were polished) measured 35-50 mm (1 ⅜ - 2 in.) thick (Figure G2).
SURFACES	The top and bottom surfaces are fracture surfaces such that the core represents a partial thickness of the column. The fractures pass consistently around aggregate particles (Figure G3). The piece used for petrography had the saw cut at the bottom and the fracture at the top.
GENERAL CONDITION	The concrete is hard and compact and rings lightly when sounded with a hammer.

2. EMBEDDED OBJECTS

GENERAL	None observed.
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3. CRACKING

MACROSCOPIC	None observed.
MICROSCOPIC	No significant microcracking observed. A few microcracks cut through the paste within 1-2 mm (40-80 mil) of the upper fracture surface (Figure G4). These are ~ 75 µm (3 mil) wide, up to 6 mm (¼ in.) long and contain minor deposits of ettringite.

4. VOIDS

VOID SYSTEM	Concrete is air-entrained and contains 4.6% air by ASTM C457 (Figure G5). The consolidation of the concrete is good with no large entrapped voids or bleed voids observed.
VOID FILLINGS	Voids commonly contain trace deposits of ettringite.

5. COARSE AGGREGATE

PHYSICAL PROPERTIES	Natural river gravel with 19 mm (¾ in.) nominal top size (Figure G6). The rocks are hard and competent. The particles are mostly oblong in shape with well-rounded to round edges but sub-equant, rounded particles are also make up a significant portion of the aggregate. The aggregate is somewhat gap graded with few intermediate-sized particles such that the concrete has a high sand content with most sand particles less than 1.18 mm (#16 sieve). The distribution is relatively even. No significant alignment of elongated particles was observed.
ROCK TYPES	The aggregate is siliceous in composition and consists primarily of metagraywackes with minor amounts of granitic rocks. Other components include quartzites and more mafic igneous rocks such as granodiorite and diorite. The metagraywackes are distinguished by very fine grained matrices and angular to sub-angular particles of feldspar and quartz. The quartzites are commonly medium-grained and range in composition from arenitic to arkosic. Many of these components are potentially susceptible to alkali-silica reaction (ASR).
OTHER FEATURES	No deleterious coatings or incrustations observed. No low w/c mortar coatings observed. No reaction rims, significant internal microcracking, deposits of gel or other evidence of ASR observed. Minor loss of paste observed around some aggregate particles; deposits of ettringite observed around aggregate (Figure G7).

APPENDIX G: CTV Building Collapse Core Petrography
 Sample ID: Core R3 (16YD5362)

Report No. DRP12.960
 Date: 10 May 2012

6. FINE AGGREGATE

PHYSICAL PROPERTIES	Natural river sand consists of rocks that are hard and competent (Figure G8). The particles are sub-equant to oblong in shape with sub-rounded to sub-angular edges. The grading and distribution are relatively even.
ROCK TYPES	The sand is mostly siliceous in composition and consists of rocks similar to those observed in the coarse aggregate, suggesting they are derived from a common geological source. The finer sieve sizes contain particles of quartz, feldspar, biotite and metallic oxide minerals.
OTHER FEATURES	No deleterious coatings or incrustations observed and no low w/c mortar coatings observed. No evidence of ASR observed.

7. PASTE OBSERVATIONS

POLISHED SURFACE	Paste ranges from light gray (Munsell 10YR/7/2) to very pale brown (10YR/7/3) when viewed macroscopically but is mottled from white to light brown when viewed at high magnification under reflected light (Figure G9). The paste has a granular to smooth texture and a sub-vitreous luster and is moderately soft (Mohs ~ 3).
THIN SECTION*	The paste contains hydrated portland cement; no fly ash, slag cement or other SCM were observed (Figure G10). The hydration is advanced with less than 3% RRCG that consist mostly of belite and interstitial aluminate and ferrite. CH makes up 15-25% of the paste, is coarse-grained and unevenly distributed. Fine crystallites of calcium carbonate also observed intermittently.
FRESH FRACTURE SURFACE	Fracture surface is light gray to pale brown, has a granular to punky texture and a dull to chalky luster. The surface cuts through ~ 10% of the aggregate.
* Abbreviations as follows: RRCG = relict and residual cement grains; SCM = supplemental cementitious materials; CH = calcium hydroxide; ITZ = interfacial transition zone. Modal abundances are based on visual estimations.	

8. SECONDARY DEPOSITS

PHENOLPHTHALEIN	Entire surface stains purple (Figure G11).
DEPOSITS	Trace to minor deposits of ettringite commonly observed in voids (Figure G12). Very minor carbonation observed in thin section.

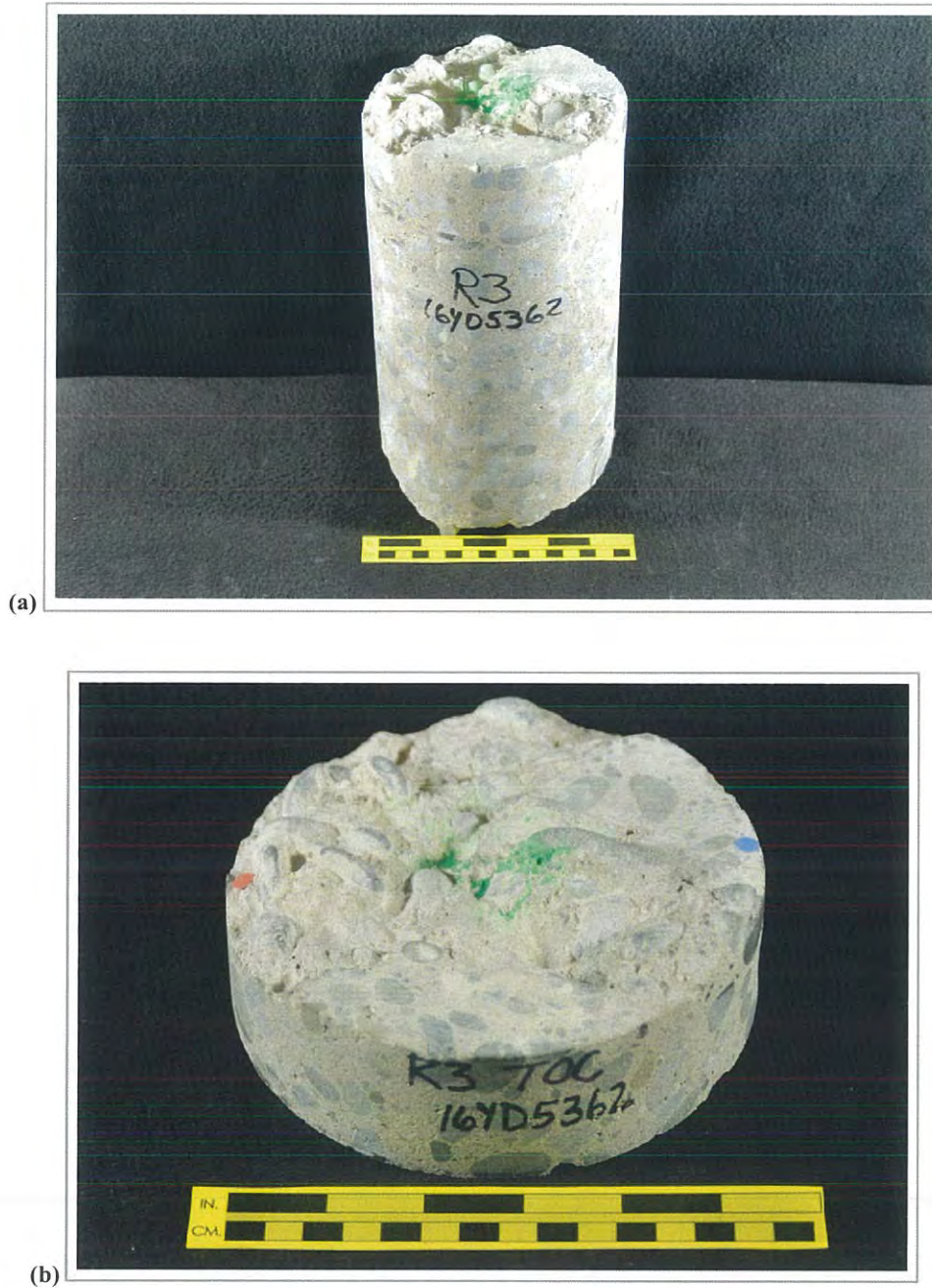
FIGURES

Figure G1. Photographs showing oblique views (a) of the top and side of the core with identification labels in the as-received condition and (b) the lower section of the core used for petrography after the core was trimmed for strength testing. The red and blue dots in (b) show the orientation of the saw cuts used to prepare the sample for petrography.

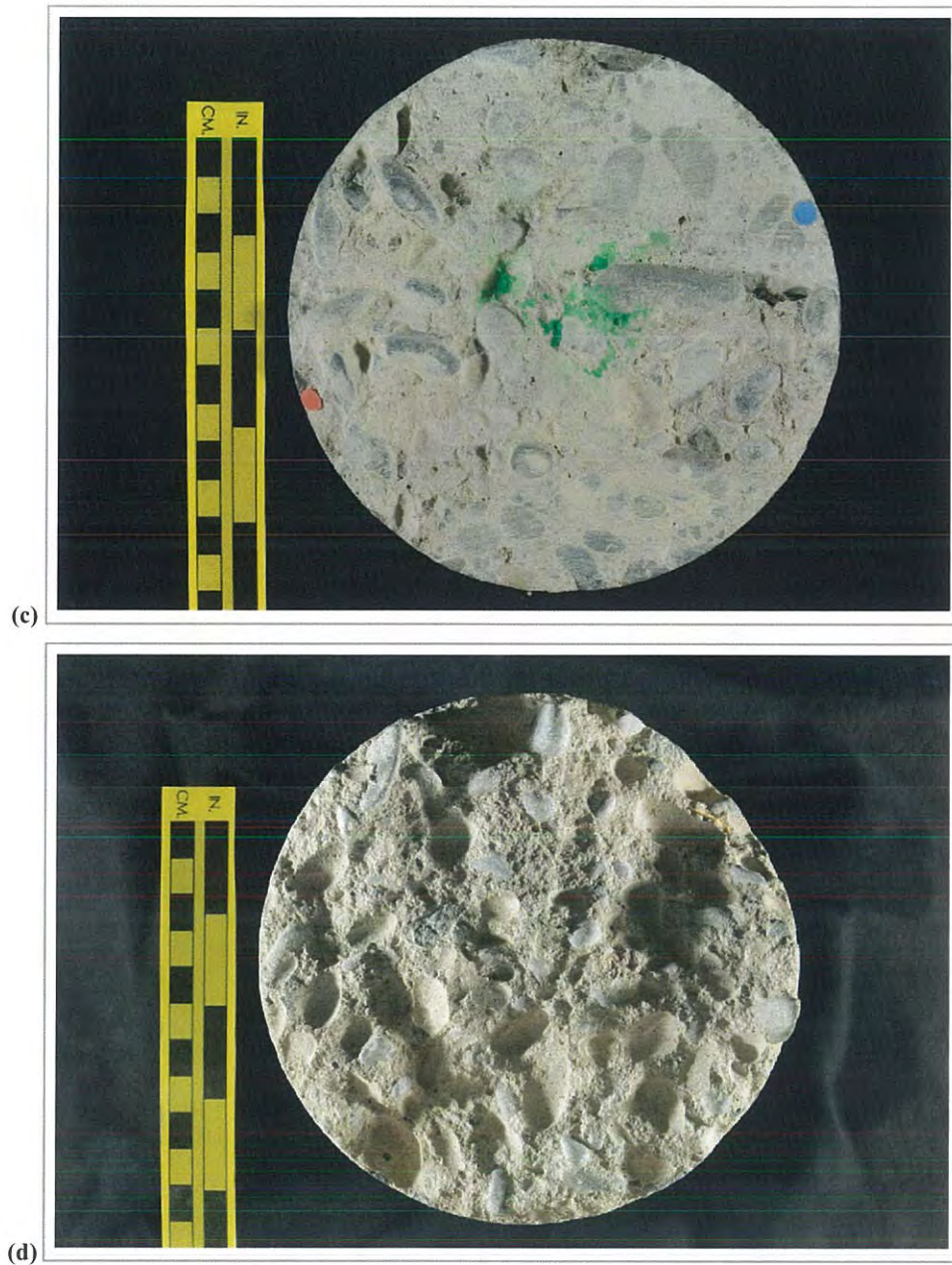


Figure G1 (cont'd). Photographs showing the (a) top and (b) bottom surfaces of the core. The section used for petrography had a saw cut surface on the bottom. The red and blue dots in (a) show the orientation of the saw cuts used to prepare the polished surface of the sample.

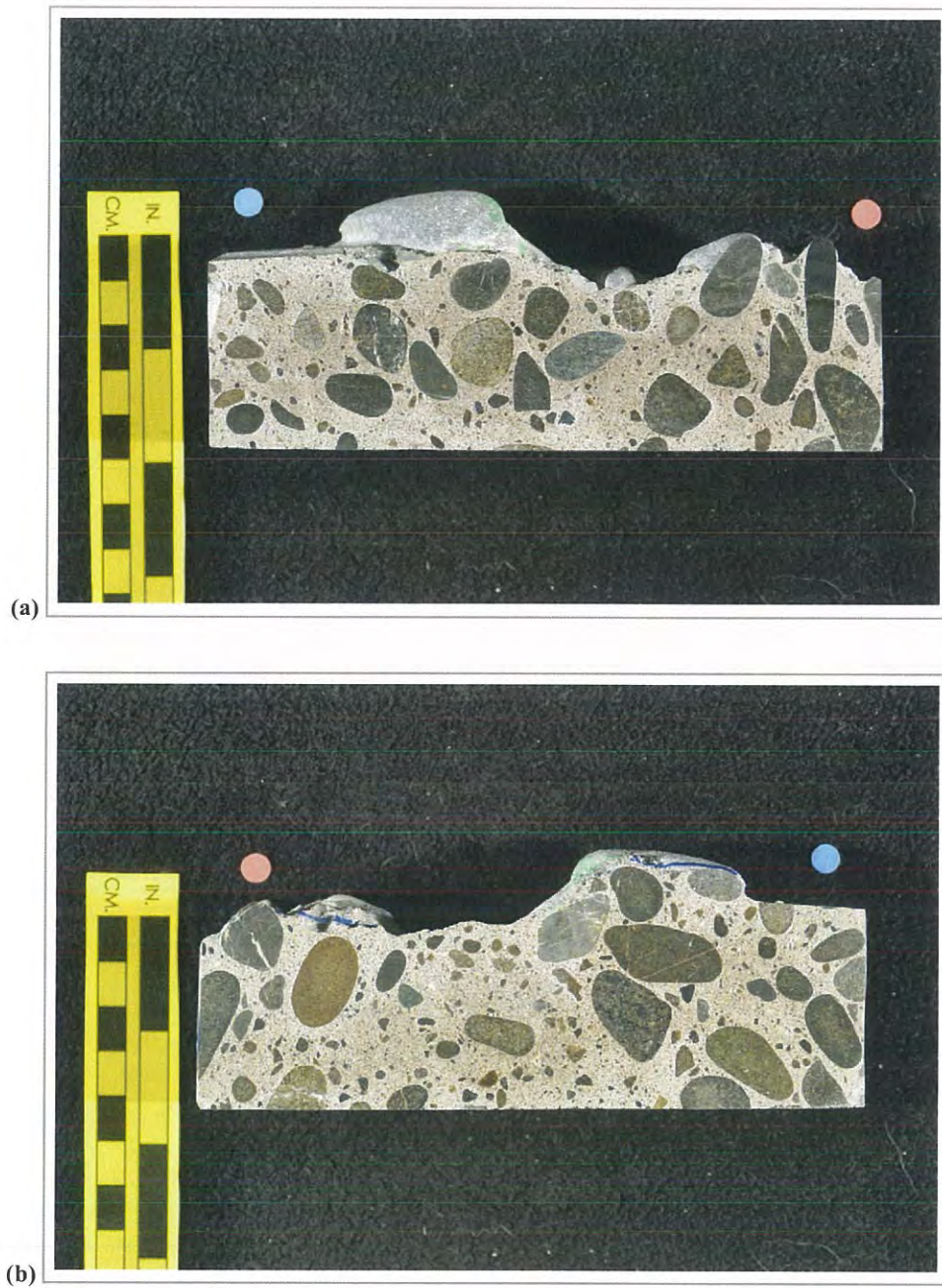


Figure G2. Photograph showing the polished surfaces of the core.

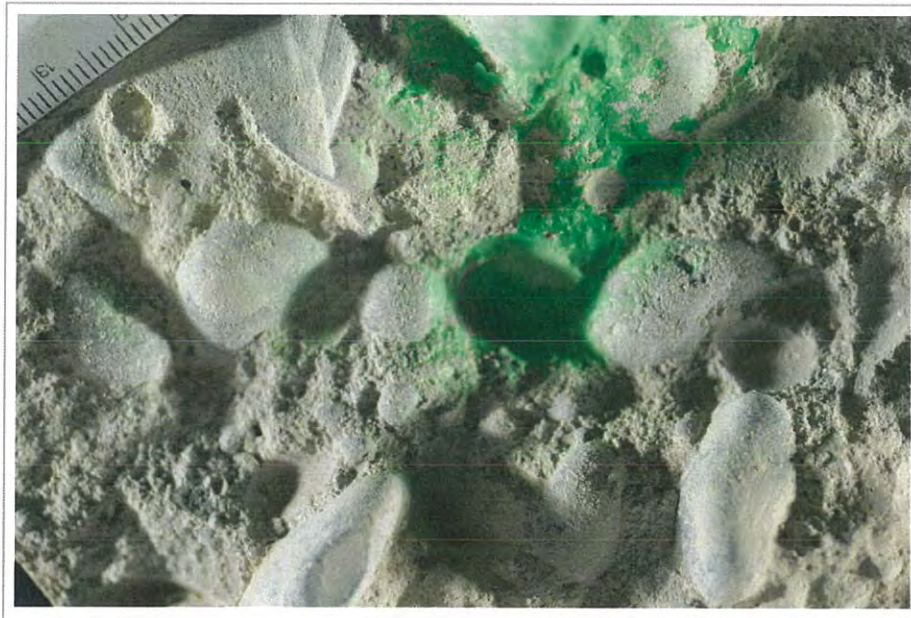


Figure G3. Photograph showing detail of the as-received top surface of the core.

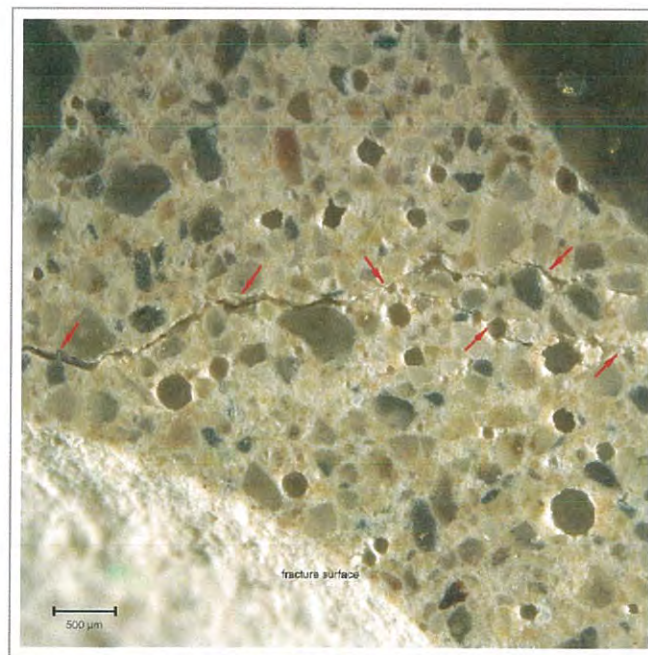


Figure G4. Reflected light photomicrograph of polished surface showing microcracks (red arrows) near the fracture surface. The orientation of the photograph was rotated 180° from the true orientation of the sample.

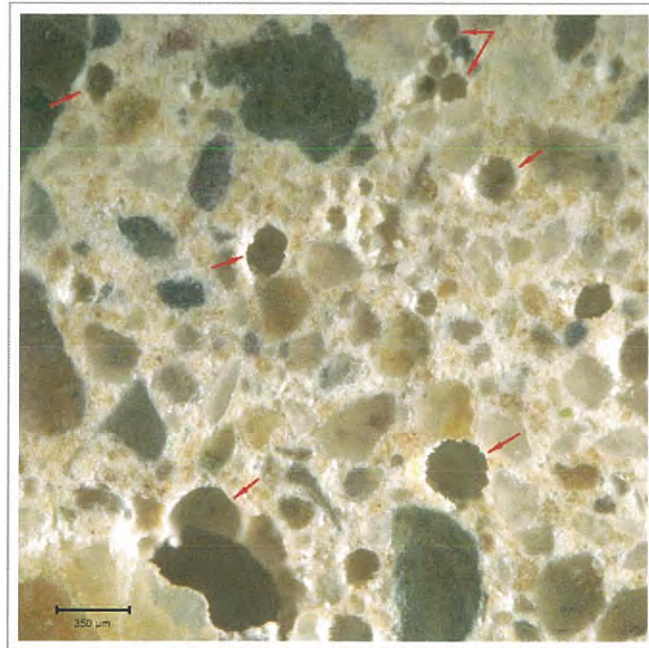


Figure G5. Oblique reflected light photomicrograph of polished surface showing voids (dark circles, with red arrows showing some examples).

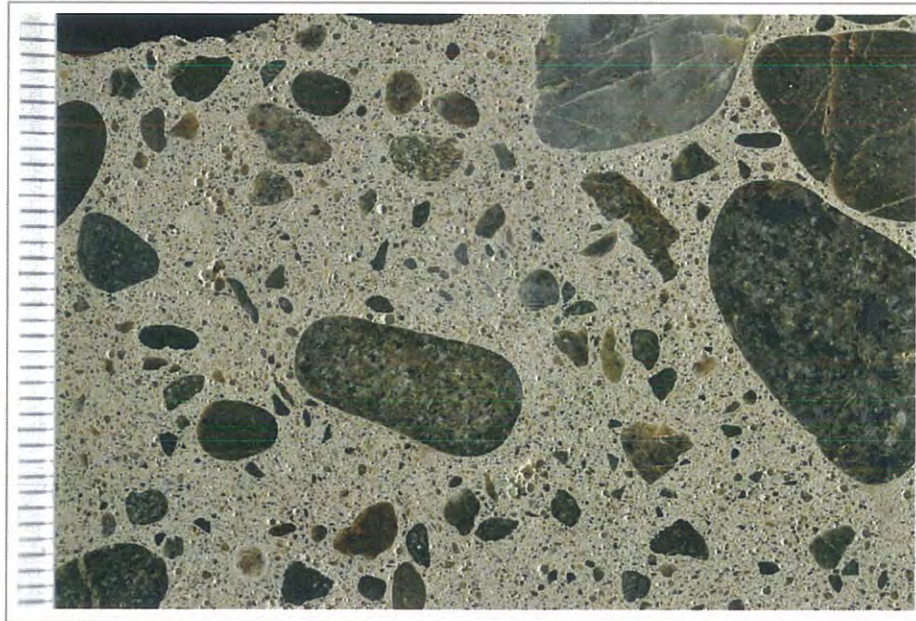


Figure G6. Photograph of the polished surface showing coarse aggregate; scale in millimeters.

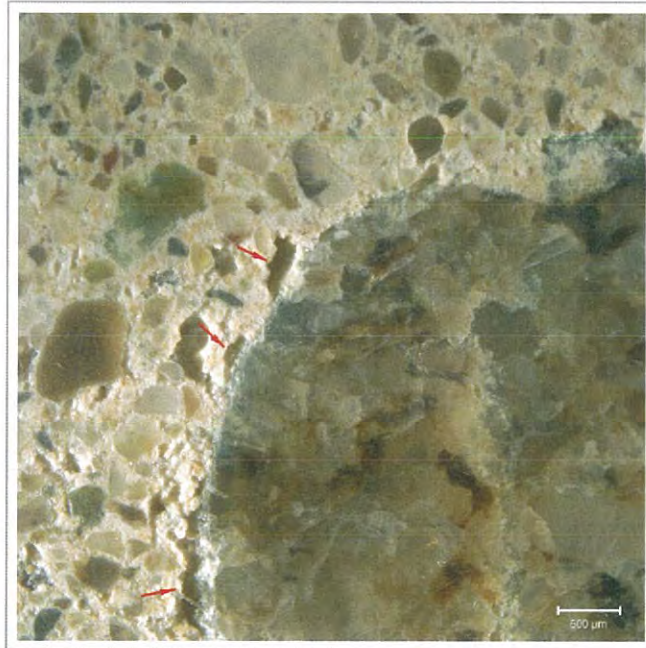


Figure G7. Reflected light photomicrograph of polished surface showing detail of paste-aggregate boundary and loss of paste around the aggregate (red arrows).

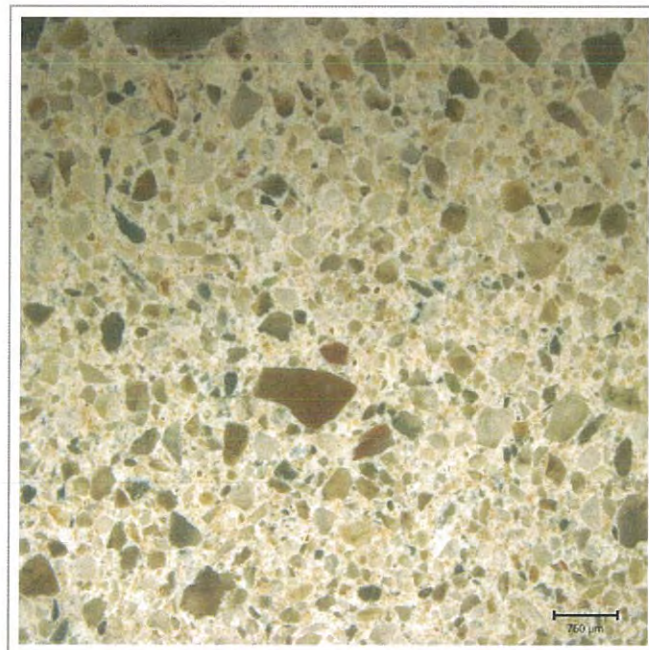


Figure G8. Reflected light photomicrograph of polished surface showing the fine aggregate.

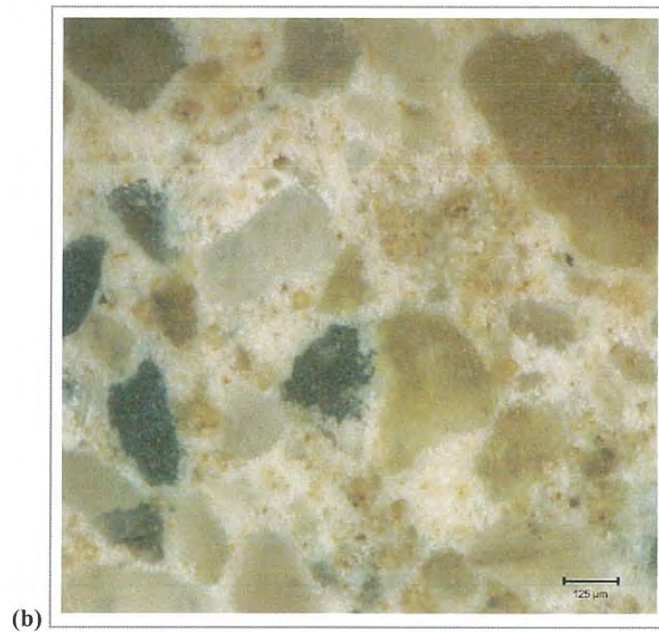
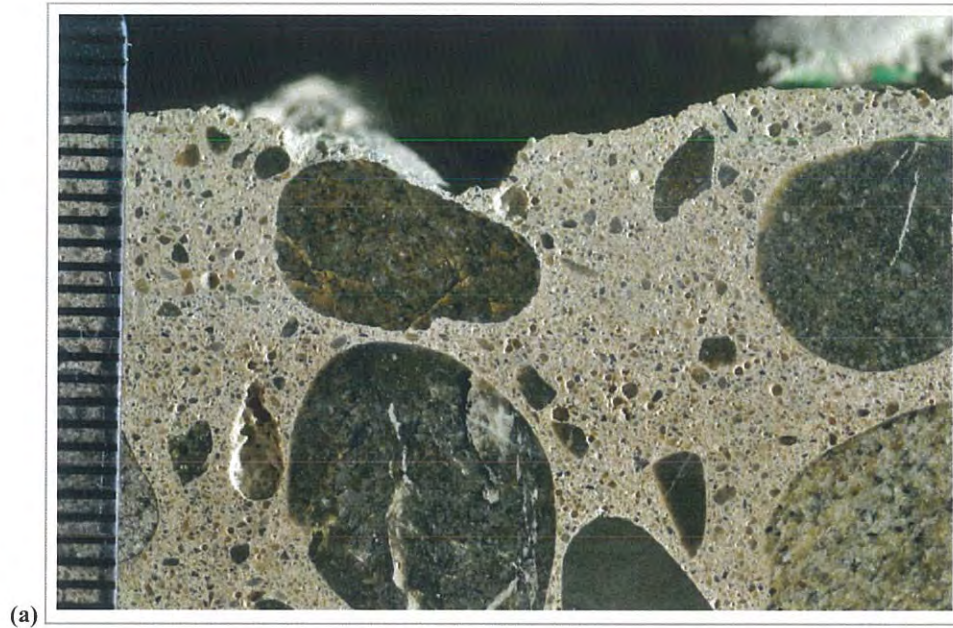


Figure G9. (a) Photograph of polished surface showing overview of paste at the top of the core. The scale is in millimeters. (b) Reflected light photomicrograph of polished surface showing detail of paste texture and luster in the middle of the petrography section of the core.

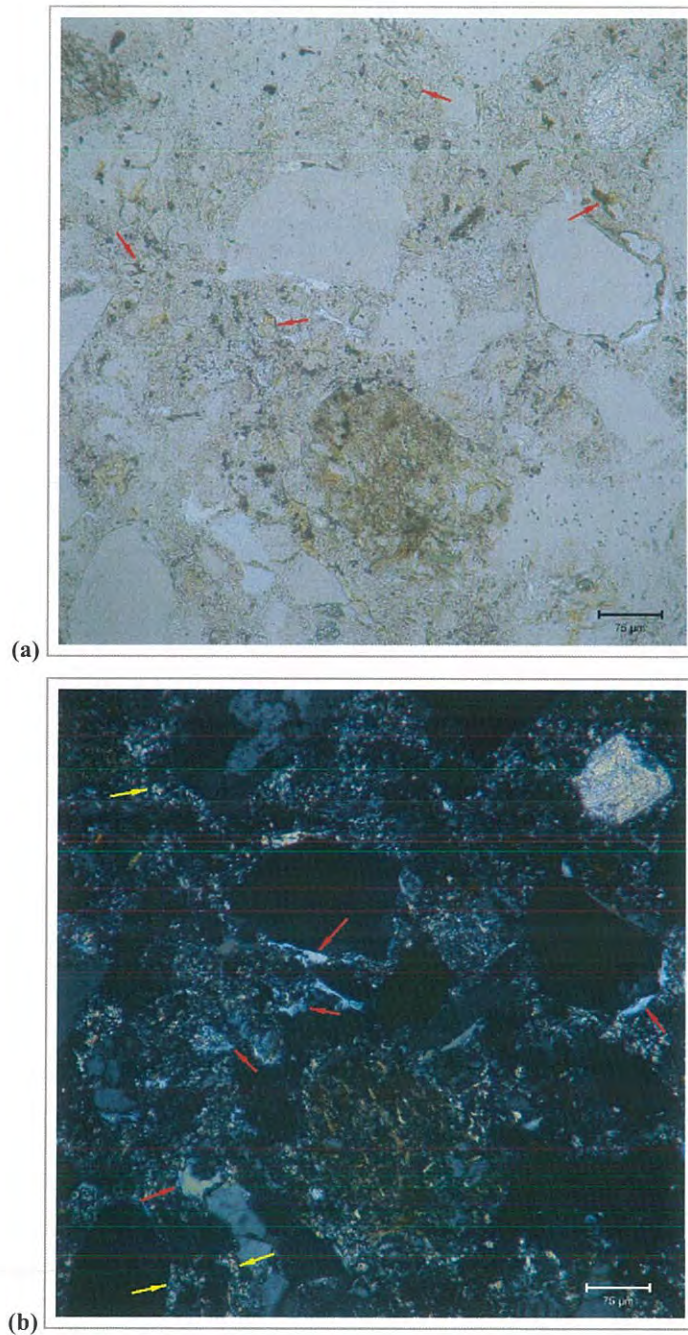


Figure G10. Transmitted light photomicrographs of thin section from the concrete core showing detail of paste in (a) plane-polarized and (b) cross-polarized light. The red arrows in (a) indicate RRCG; in (b) they indicate CH. The yellow arrows in (b) highlight crystallites of calcium carbonate.

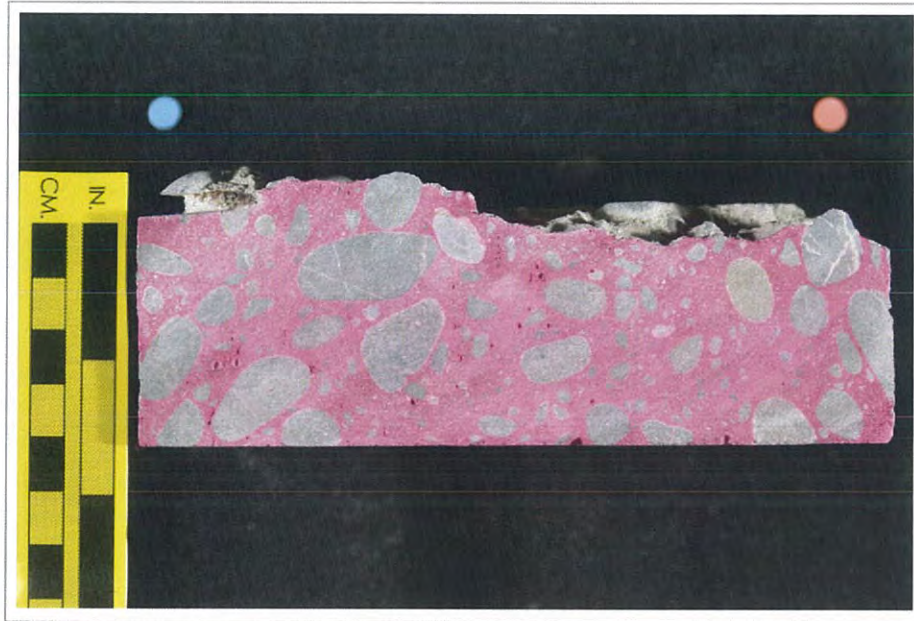


Figure G11. Photograph showing phenolphthalein stained surface.

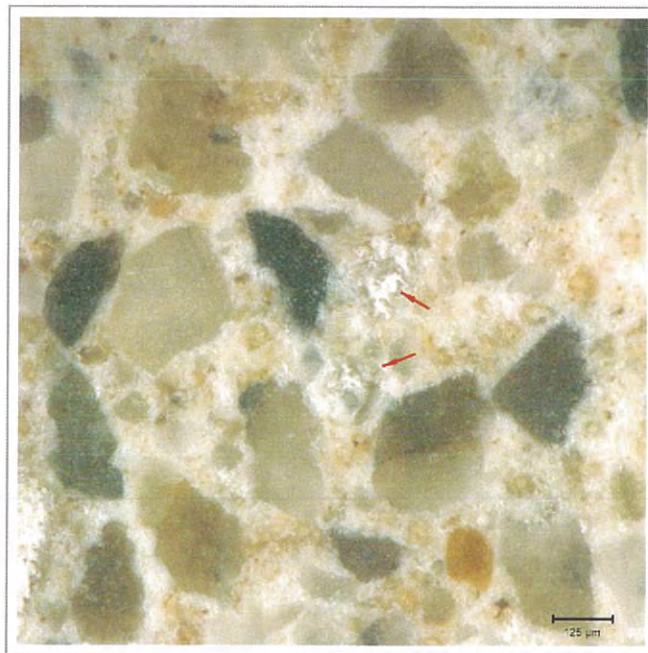


Figure G12. Reflected light photomicrograph of polished surface showing trace deposits of ettringite (red arrows) in fine air voids. Such deposits were observed commonly.

APPENDIX H: CTV Building Collapse Core Petrography
 Sample ID: Core R7 (16YD5363)

Report No. DRP12.960
 Date: 10 May 2012

I. RECEIVED CONDITION

ORIENTATION	Vertical core taken through center of recovered column measures 145 mm (5 ¾ in.) in diameter and 330 mm (13 in.) in length (Figure H1). The core was received in two pieces with the break occurring 235-265 mm (9 ¼ - 10 ⅜ in.) below the top surface. After trimming the core for strength testing two pieces were obtained for petrographic examination. One piece measured about 80 mm (3 ⅛ in.) thick and the other measured about 40 mm (1 ⅝ in.) thick.
SURFACES	The top and bottom surfaces have a saw cut over most of them with a fracture in the center of the surfaces, such that the core represents a partial thickness of the column (Figure H2). The bottom of the top piece and top of the bottom piece are fracture surfaces that pass consistently around aggregate particles and the fractured sections of the top and bottom surfaces also pass around aggregates (Figure H3). The piece used for petrography from the upper section of the core had the saw cut at the top and a fracture at the bottom and the piece from the bottom of the core had fractures at the top and bottom (Figure H4).
GENERAL CONDITION	The concrete is hard and compact and rings lightly when sounded with a hammer.

2. EMBEDDED OBJECTS

GENERAL	None observed.
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3. CRACKING

MACROSCOPIC	None observed.
MICROSCOPIC	No significant microcracking observed.

4. VOIDS

VOID SYSTEM	Concrete is not air-entrained and contains 2.0% air by ASTM C457 (Figure H5). The point count analysis was done on the section from the bottom of the core. The concrete is well-consolidated in that no large entrapped voids or bleed voids observed.
VOID FILLINGS	Voids are mostly free of secondary deposits, rare to occasional voids contain trace deposits of ettringite.

APPENDIX H: CTV Building Collapse Core Petrography
 Sample ID: Core R7 (16YD5363)

Report No. DRP12.960
 Date: 10 May 2012

5. COARSE AGGREGATE

PHYSICAL PROPERTIES	Natural river gravel with 19 mm ($\frac{3}{4}$ in.) nominal top size (Figure H6). The rocks are hard and competent. The particles are mostly oblong in shape with well-rounded to round edges but sub-equant, rounded particles are also make up a significant portion of the aggregate. The aggregate is gap graded with few intermediate-sized particles such that the concrete has a high sand content with most sand particles less than 1.18 mm (#16 sieve). The distribution is somewhat uneven as the section from the lower portion of the core shows less fine sand than the section from the top of the core (Figure H4, H6). No significant alignment of elongated particles was observed.
ROCK TYPES	The aggregate is siliceous in composition and consists primarily of metagraywackes with minor amounts of granitic rocks. Other components include quartzites and more mafic igneous rocks such as granodiorite and diorite. The metagraywackes are distinguished by very fine grained matrices and angular to sub-angular particles of feldspar and quartz. The quartzites are commonly medium-grained and range in composition from arenitic to arkosic. Many of these components are potentially susceptible to alkali-silica reaction (ASR).
OTHER FEATURES	No deleterious coatings or incrustations observed. No low w/c mortar coatings observed. No reaction rims, significant internal microcracking, deposits of gel or other evidence of ASR observed.

6. FINE AGGREGATE

PHYSICAL PROPERTIES	Natural river sand consists of rocks that are hard and competent (Figure H7). The particles are sub-equant to oblong in shape with sub-rounded to sub-angular edges. The grading and distribution are relatively even.
ROCK TYPES	The sand is mostly siliceous in composition and consists of rocks similar to those observed in the coarse aggregate, suggesting they are derived from a common geological source. The finer sieve sizes contain particles of quartz, feldspar, biotite and metallic oxide minerals.
OTHER FEATURES	No deleterious coatings or incrustations observed and no low w/c mortar coatings observed. No evidence of ASR observed.

7. PASTE OBSERVATIONS

POLISHED SURFACE	Paste is light gray (Munsell 10YR/7/2) to gray (10YR/6/1) when viewed macroscopically but is mottled from white to light brown when viewed at high magnification under reflected light (Figure H8). The paste has a smooth texture and a sub-vitreous luster. The paste is moderately hard (Mohs ~ 3.5).
THIN SECTION*	The paste contains hydrated portland cement; no fly ash, slag cement or other SCM were observed (Figure H9). The hydration is normal to advanced with 3-5% RRCG that consist mostly of belite and interstitial aluminate and ferrite. CH makes up 15-25% of the paste, is medium to coarse-grained and unevenly distributed.
FRESH FRACTURE SURFACE	Fracture surface is light gray to pale brown, has a granular to punky texture and a dull to chalky luster. The surface cuts through ~ 15% of the aggregate.
* Abbreviations as follows: RRCG = relict and residual cement grains; SCM = supplemental cementitious materials; CH = calcium hydroxide; ITZ = interfacial transition zone. Modal abundances are based on visual estimations.	

8. SECONDARY DEPOSITS

PHENOLPHTHALEIN	Entire surface stains purple (Figure H10).
DEPOSITS	Trace deposits of ettringite occasionally observed in voids. Very minor carbonation observed.

FIGURES

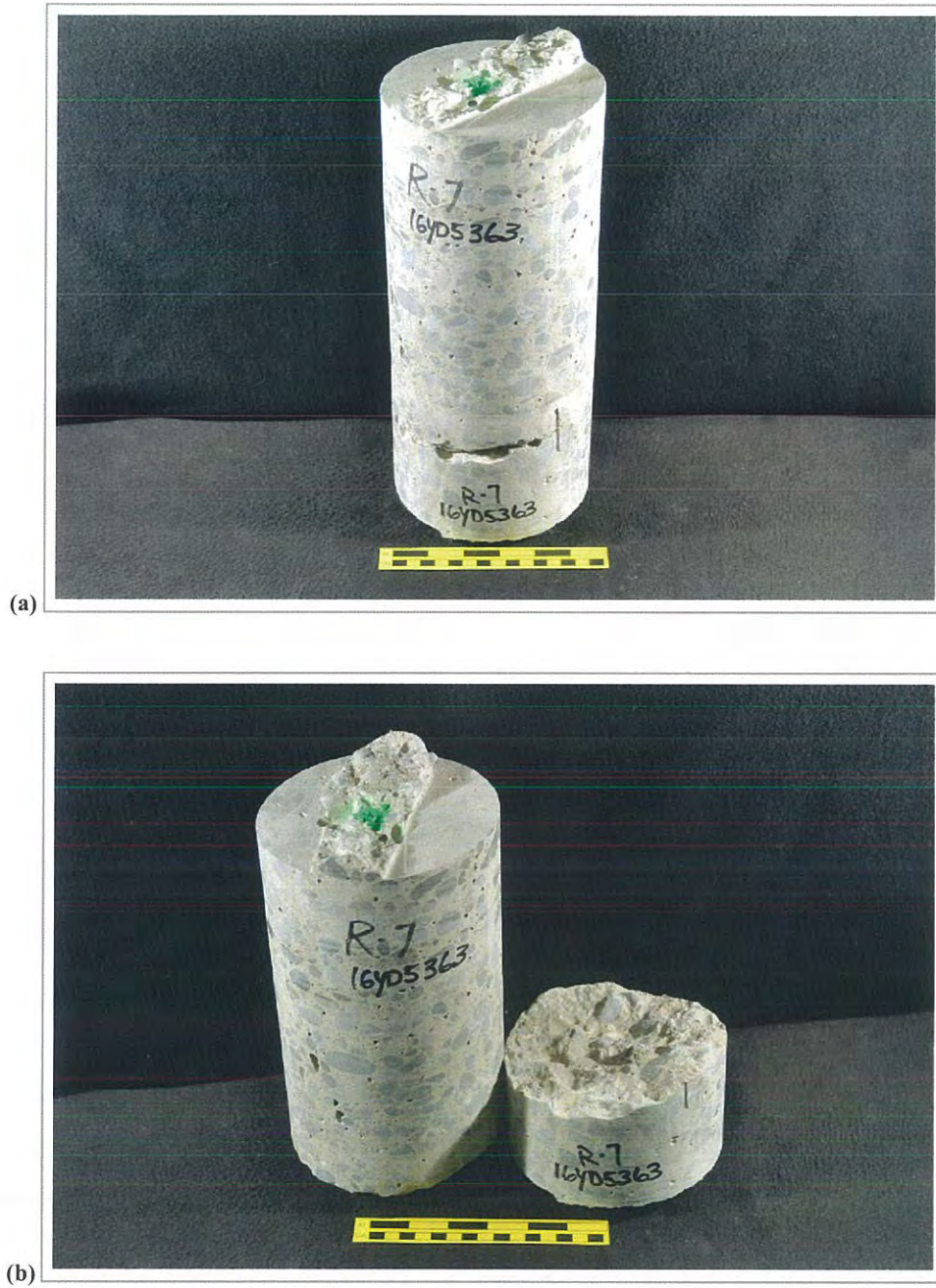


Figure H1. Photographs showing oblique views of the top and side of the core with identification labels.

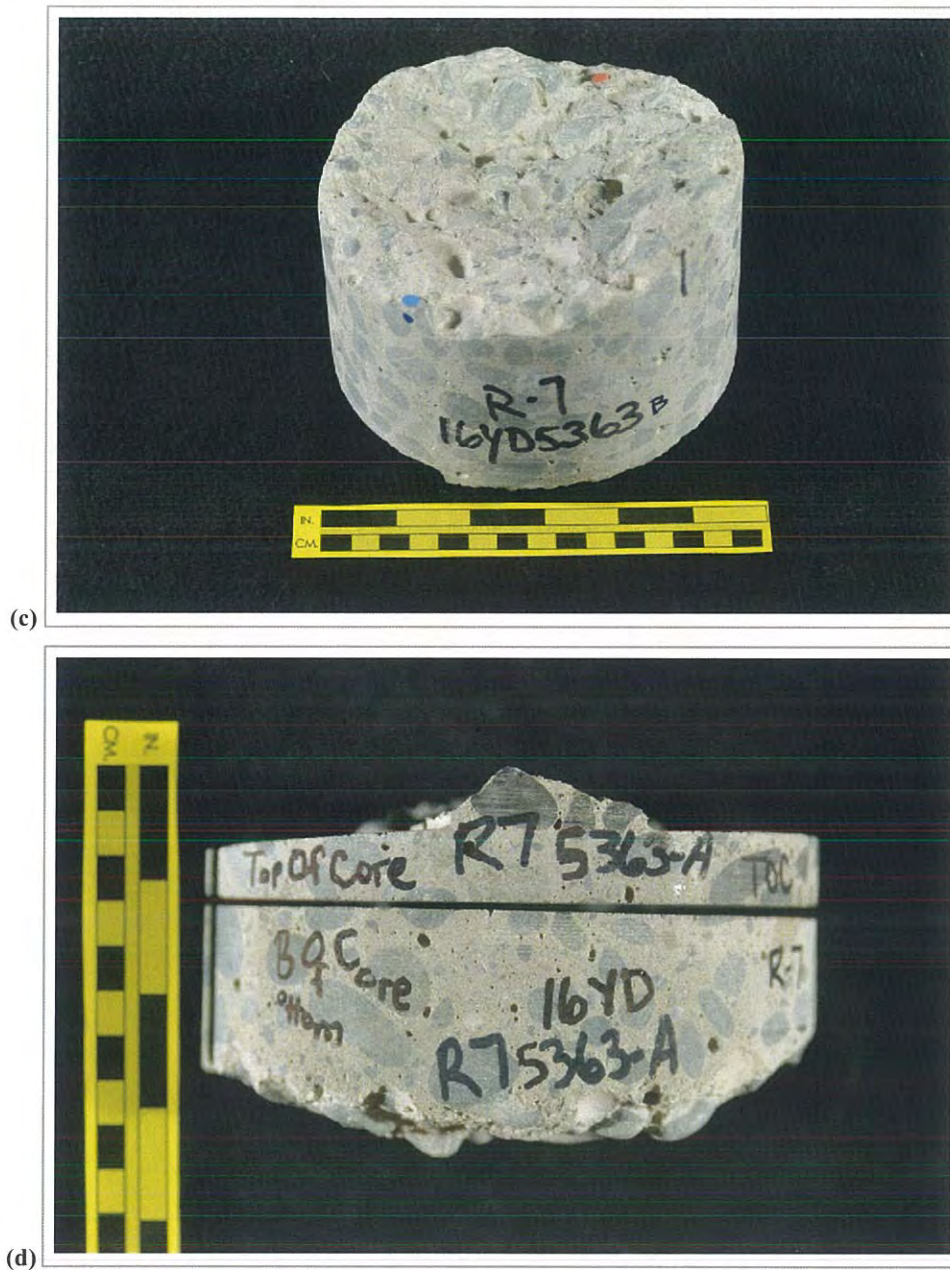


Figure H1 (cont'd). (c) Photograph showing the top and side of the lower piece of the core in as-received condition. (d) Photograph showing side of the upper portion of the core after it was trimmed for strength testing. The lower portion of the upper section was prepared for reflected light microscopy.

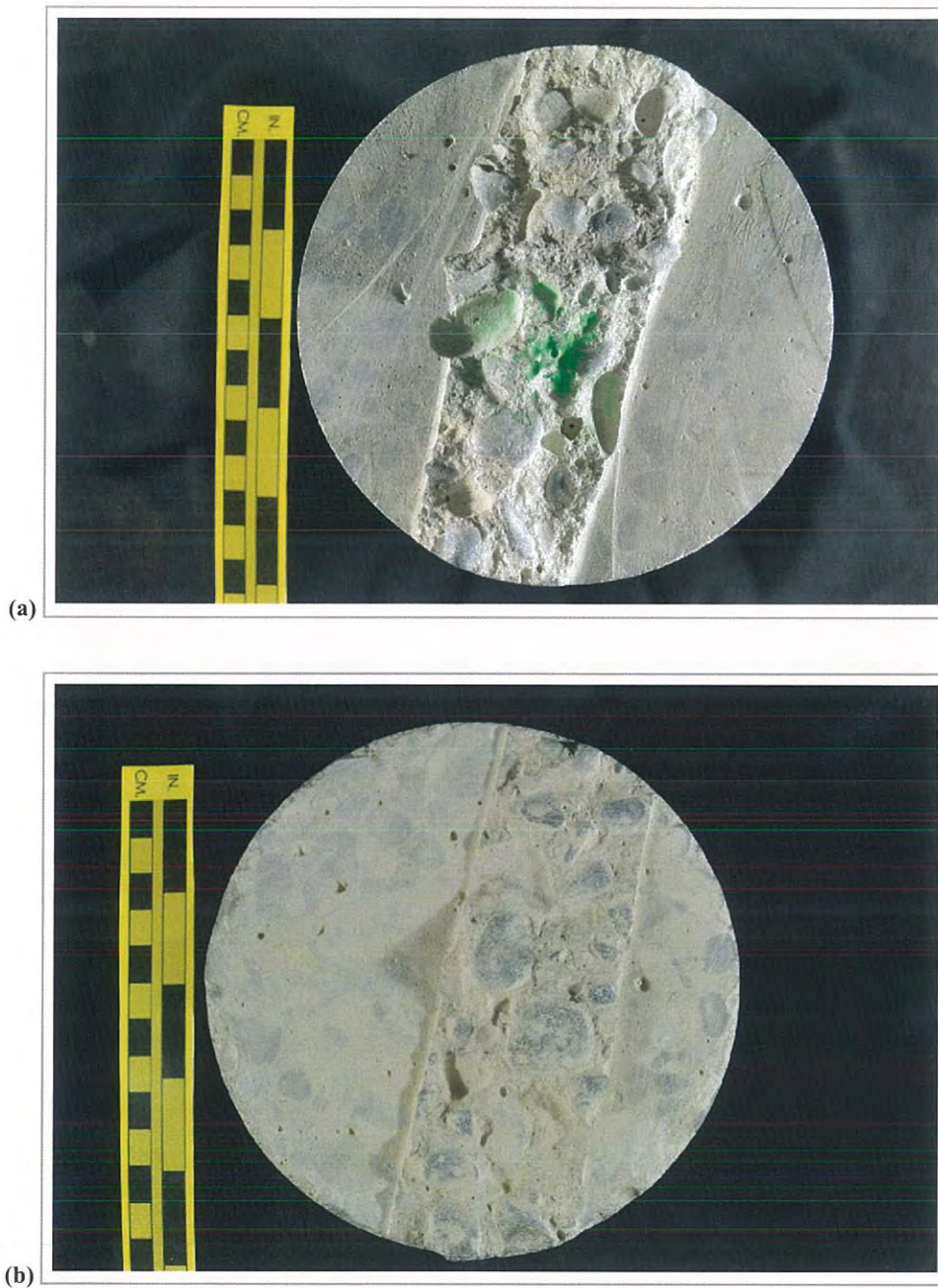


Figure H2. Photographs showing the as-received (a) top and (b) bottom surfaces of the core.



Figure H3. Photographs showing the as-received fracture surface that separated the core into two pieces. The bottom fracture surface of the top piece is shown in (a) and (b) shows the top fracture surface of the bottom piece. Scale in millimeters in both photos.

APPENDIX H: CTV Building Collapse Core Petrography
Sample ID: Core R7 (I6YD5363)

Report No. DRP12.960
Date: 10 May 2012

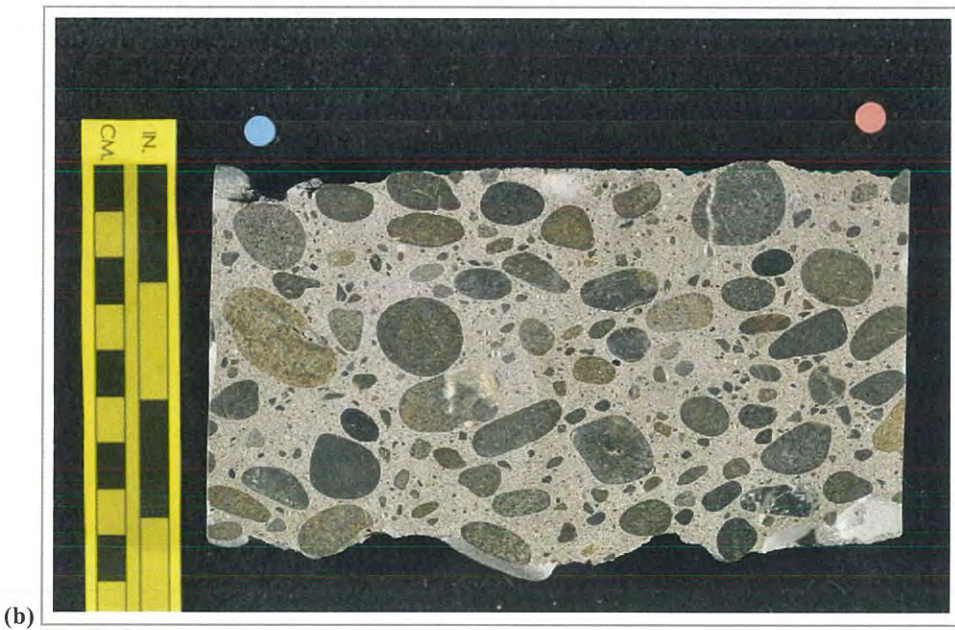


Figure H4. Photographs showing the polished surfaces from the (a) top section and (b) bottom section of the core.

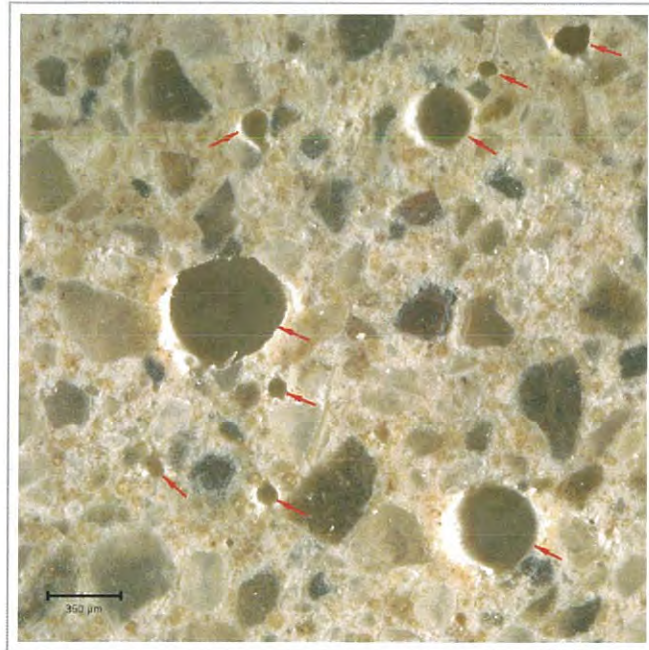


Figure H5. Oblique reflected light photomicrograph of polished surface showing view of voids (red arrows).



Figure H6. (a) Photograph of the polished surface from the top portion of the core showing coarse aggregate; scale in millimeters.

APPENDIX H: CTV Building Collapse Core Petrography
Sample ID: Core R7 (I6YD5363)

Report No. DRP12.960
Date: 10 May 2012



Figure H6 (cont'd). (b) Photograph of the polished surface from the bottom portion of the core showing coarse aggregate; scale in millimeters.

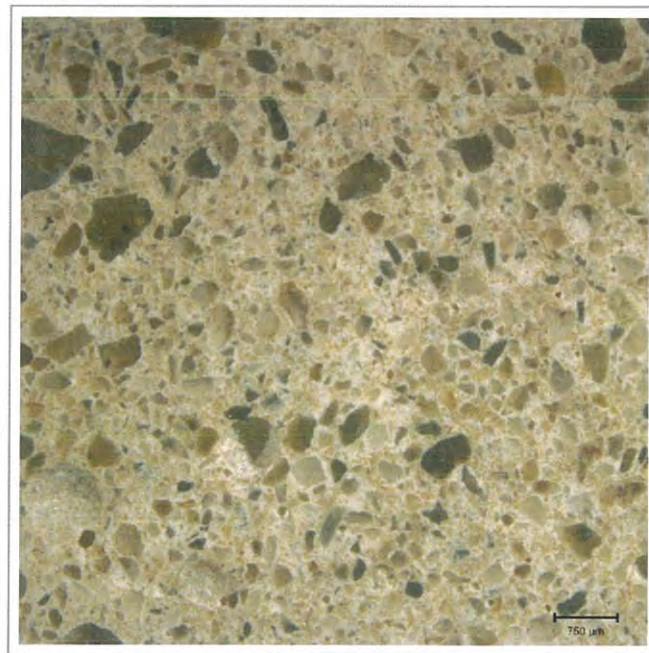


Figure H7. Reflected light photomicrograph of polished surface showing the fine aggregate.

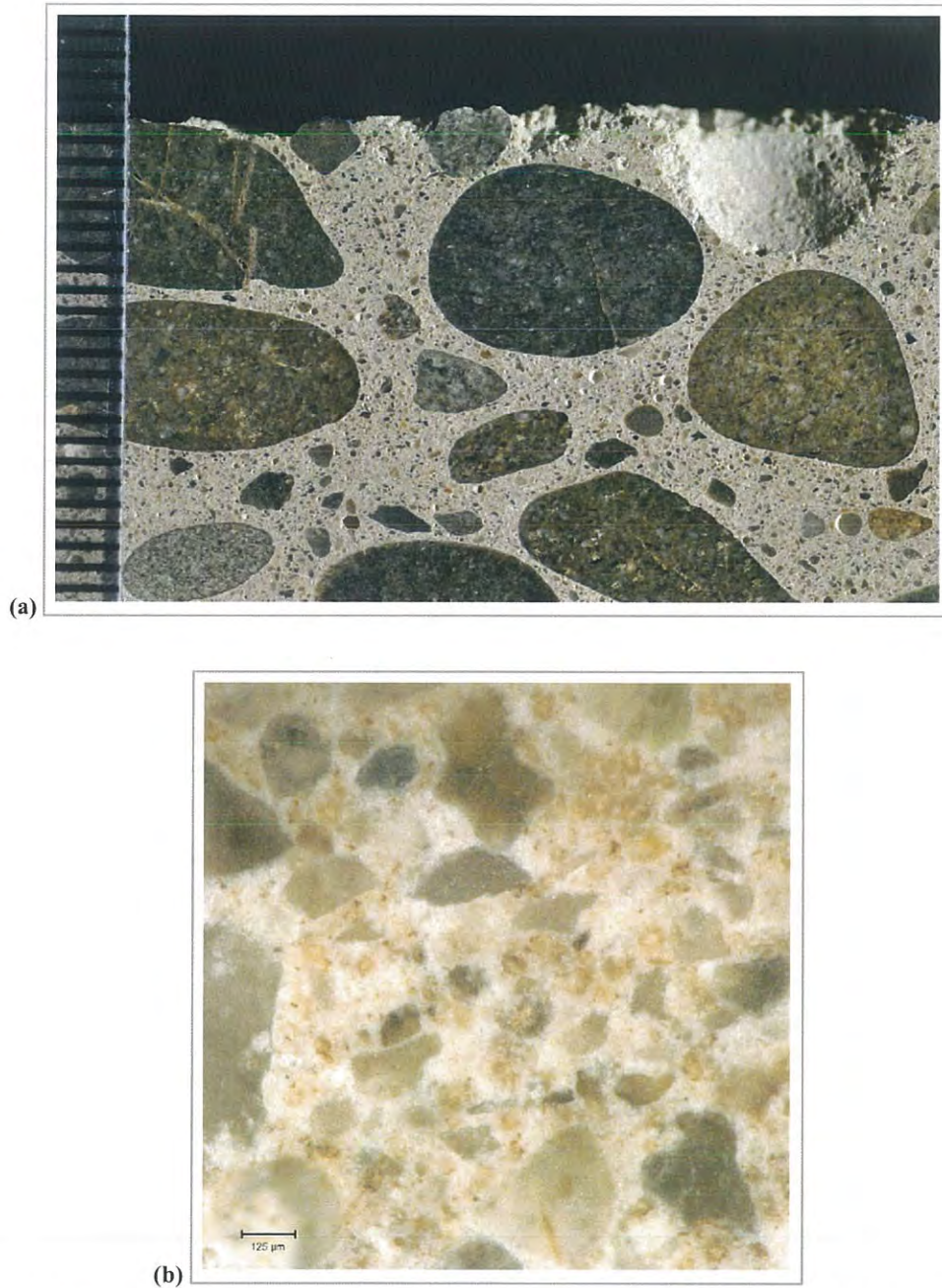


Figure H8. (a) Photograph showing overview of paste at the top of the bottom section of the core. The scale is in millimeters. (b) Reflected light photomicrograph of polished surface showing detail of paste texture and luster taken in the middle of the bottom section of the core.

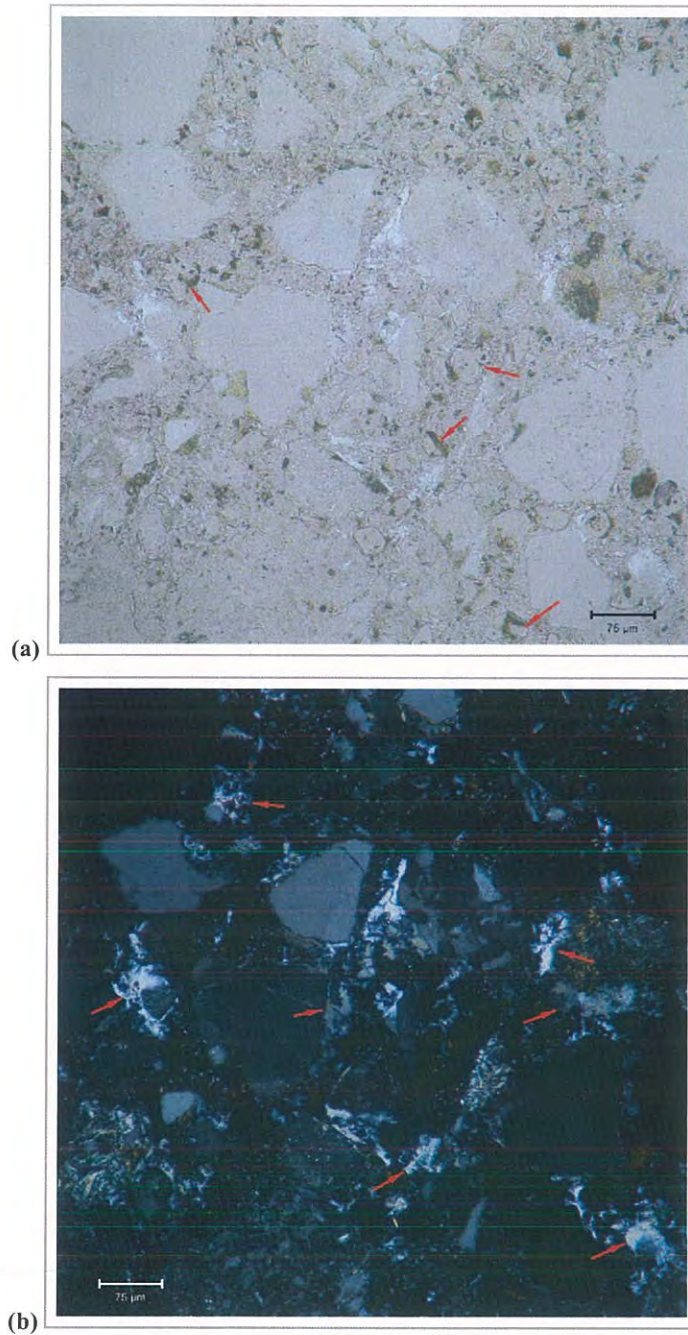


Figure H9. Transmitted light photomicrographs of thin section from the concrete core showing detail of paste in (a) plane-polarized and (b) cross-polarized light. The red arrows in (a) indicate RRCG; in (b) they indicate CH.

APPENDIX H: CTV Building Collapse Core Petrography
Sample ID: Core R7 (I6YD5363)

Report No. DRP12.960
Date: 10 May 2012

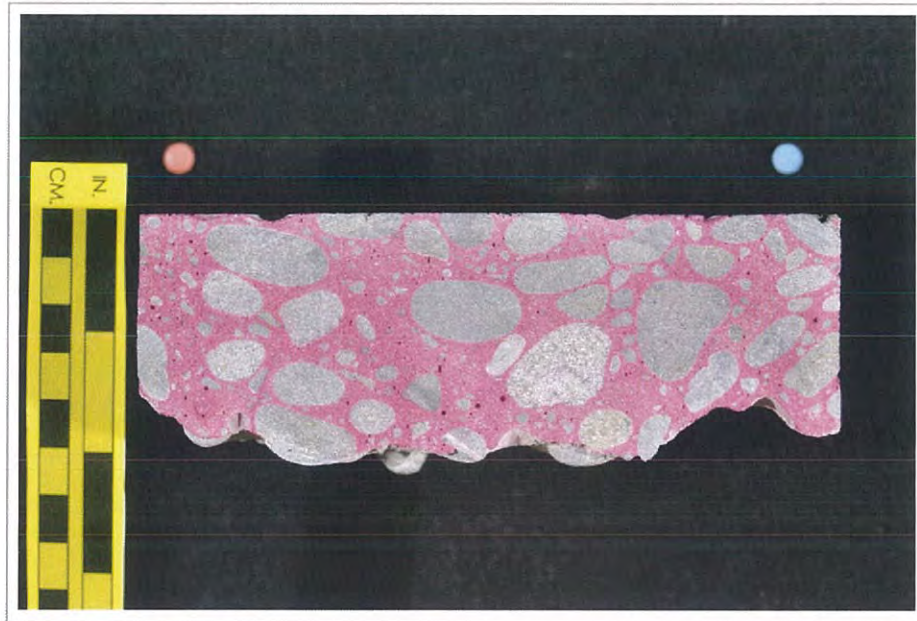


Figure H10. Photograph showing phenolphthalein stained surface from the top section of the core.

Table I1. Results of ASTM C457 Testing

Measured Parameters	C1 T ½	C4 T ½	C7 T ½	C12 B ½	R3	R7
Aggregate Stops	951	948	1026	943	900	970
Paste Stops (S _p)	374	392	322	405	393	365
Air Stops (S _a)	27	20	14	26	62	27
Total Stops (S _t)	1352	1360	1362	1374	1355	1362
Calculated Parameters	C1 T ½	C4 T ½	C7 T ½	C12 B ½	R3	R7
Traverse Length (T _t ; in.)	101.4	102.0	102.2	103.1	101.6	102.2
Traverse Length (T _t ; mm)	2576	2591	2595	2617	2581	2595
Aggregate Content	70.3%	69.7%	75.3%	68.6%	66.4%	71.2%
Paste Content (p)	27.7%	28.8%	23.6%	29.5%	29.0%	26.8%
Air Content (A)	2.0%	1.5%	1.0%	1.9%	4.6%	2.0%
Paste-Air Ratio (p/A)	13.9	19.6	23.0	15.6	6.3	13.5
<i>Note: Analyses done via the Point-Count Method (Method B) in ASTM C457 using a stepping distance of 1.905 mm (0.075 in.) at 120x magnification. The analysis complies with the following requirements for calculating air content for concrete with 19 mm (¾ in.) aggregate: 1350 points, traverse length of 2286 mm (90 in.), and traverse area of 71 cm² (11 in²).</i>						

PROCEDURES

ASTM C856--Petrographic Analysis The petrographic work was done following ASTM C856 [1] with sample preparation done at **DRP** in the following manner. After writing the unique **DRP** sample number on each sample near the received label, the samples were measured and inspected visually and with a hand lens. The orientation of the saw cuts used to prepare the samples was then indicated on each sample with blue and red dots. The samples were then photographed in their as-received condition.

A slab representing a longitudinal cross section of each sample was cut from the central portion of the core using a Diamond Pacific® TR-24, a 24-inch diameter oil-lubricated saw. This produced three (3) longitudinal sections for each core. These sections rinsed in an aqueous solution with a detergent to remove the cutting oil and oven dried overnight in a Gilson® Bench Top laboratory oven at ~ 40°C (~ 105°F) to remove remaining traces of the oil. After drying, each piece was labelled with the appropriate **DRP** sample number. One piece was set aside for phenolphthalein staining and the other was set aside for thin section preparation.

The central slab was then lapped and polished on a Diamond Pacific® RL-18 Flat Lap machine. This machine employs an 18-inch diameter cast iron plate onto which Diamond Pacific® Magnetic Nova Lap discs with progressively finer grits are fixed. The Nova Lap discs consist of a 1/16 in. backing of solid rubber containing magnetized iron particles that is coated with a proprietary Nova resin-bond formula embedded with industrial diamonds of specific grit. The slab preparation involved the use of progressively finer wheels to a 3000 grit (~4 µm) final polish following procedures outlined in ASTM C457 [2]. An aqueous lubricant is used in the lapping and polishing process. The polished slab from each sample was examined visually and with a Nikon® SMZ-1500 stereomicroscope with 3-180x magnification capability following to the standard practice set forth in ASTM C856.

Phenolphthalein was applied to a freshly saw-cut surface from each sample to assess the extent of carbonation, along with thin section analysis. Phenolphthalein is an organic stain that colors materials with pH of greater than or equal to ~ 9.5 purple. Portland cement concrete generally has a pH of ~ 12.5. Carbonation lowers the pH of the paste below 9.5, so areas not stained by phenolphthalein are an indicator of carbonation. The depth of paste not stained by phenolphthalein was measured from each exposed surface.

Petrographic thin sections were prepared by cutting billets from the remaining longitudinal sections. Outlines marking the area of the billets were drawn with a marker on the saw-cut surface after visual and microscopical examination of saw-cut and polished surfaces. The billets were labeled with the unique **DRP** number assigned to the sample and impregnated with epoxy. The impregnated billets

1 *Standard Practice for Petrographic Examination of Hardened Concrete*. Annual Book of ASTM Standards, Vol. 4.02., ASTM C856-04.

2 *Standard Test Method for Microscopical Determination of Parameters of the Air-Void System in Hardened Concrete*, Annual Book of ASTM Standards, Vol. 4.02, ASTM C457-10.

were then fixed to glass slides with epoxy. After the epoxy cured, the slide was trimmed and ground on a Buehler® Petro-Thin device to a thickness of $\sim 30\ \mu\text{m}$ (1.2 mil). The slide was then moved to a Buehler® Beta-Vector machine and polished to a final thickness of $\sim 20\ \mu\text{m}$. The grinding and polishing of the thin sections were done in a non-aqueous environment. The thin sections were examined with a Nikon® E-Pol 600 petrographic microscope equipped to provide a 50-1000x magnification range following the standard practice set forth in ASTM C856.

Microscopical Hardened Air Content Determination (ASTM C457) Following the preparation of the polished surfaces as described above, the modified point-count method outlined in ASTM C457 was done to determine the hardened air content of the concrete represented by the cores. The analysis was done under oblique illumination at a magnification of 125x with a stepping distance of 1.9 mm (0.075 in.) between traverse points. Each point was tabulated and recorded as a void, aggregate particle, or paste to allow the determination of the volumetric proportions of air, aggregate, and paste, respectively.

APPENDIX IV

ULTRASONIC PULSE VELOCITY

NONDESTRUCTIVE TESTING INVESTIGATION

OLSON ENGINEERING

MAY 4, 2012

INFRASTRUCTURE IMAGING AND NDE
ASSESSMENT, MONITORING AND REPAIR



Corporate Office:
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May 4, 2012

DRP Consulting, Inc.
3200 Carbon Place #104
Boulder, CO 80301

Attn: Mr. David Rothstein
Email: petro@drpcinc.com
Tel: 303.938.0166
Fax: 303.938.0167

Re: Proposed Nondestructive Testing Investigation
Ultrasonic Pulse Velocity
CTL Thompson - Commercial Testing Labs
Denver, Colorado
Olson Job No. 3940A

Mr. Rothstein,

This letter is in reference to the nondestructive testing and evaluation (NDT&E) investigation conducted at the above referenced project in Denver, CO on May 3, 2012. Ultrasonic Pulse Velocity (UPV) services were performed by Mr. Colin Leek, Project Engineer of our firm. This letter confirms that the NDT&E work has been completed with all results listed within Table I.

Note all length and diameter measurements were provided by CTL Thompson, with brief verification by our onsite engineer. Also note that all tests were conducted on center and across each noted length.

Core#	Length (in.)	Length Test File	Length Velocity Result (ft/sec)	Diameter (in.)	Diameter Test File	Diameter Velocity Result (ft/sec)
CIT 1/2	6.13	CIT1_2-L.tfs	13,098	5.65	CIT1_2-D.tfs	13,078
C1-B	7.55	C1-B-L.tfs	12,725	5.65	C1-B-D.tfs	12,336
C4-T	5.65	C4-T-L.tfs	14,267	5.65	C4-T-D.tfs	13,848
C4-B	4.14	C4-B-L.tfs	14,374	5.65	C4-B-D.tfs	13,452
C7-T	7.52	C7-T-L.tfs	12,287	5.66	C7-T-D.tfs	12,747
C12-B	3.93	C12-B-L.tfs	13,100	5.65	C12-B-D.tfs	12,390
R-3	7.40	R3-L.tfs	12,091	5.65	R3-D.tfs	12,725
R-7	7.47	R7-L.tfs	12,450	5.65	R7-D.tfs	12,725

Table I. Notice each core velocity result, across both the length and diameter of the core, is above 12,000 ft/sec which is the typical velocity for concrete considered to be of Sound condition.

CLOSURE

The field portion of this NDT&E investigation was performed in accordance with generally accepted testing procedures. If we can provide additional information or services on this project, or additional information becomes available that would impact the findings of this investigation, please call.

Respectfully submitted,

Olson Engineering, Inc.


Colin O. Leek
Project Engineer
Dennis A. Sack, P.E.
Sr. Vice President, Associate Engineer

(1 copy emailed and 2 copies mailed)

APPENDIX V

CONCRETE CORE TEST RESULTS

CTV BUILDING COLLAPSE INVESTIGATION

CTL | THOMPSON

MAY 25, 2012



May 25, 2012

BuddleFindlay
245 St Asaph Street
PO Box 322
Christchurch 8140
New Zealand DX WP20307

Attention: Willie Palmer, Esq.

Douglas J. Haavik, Consulting Engineer
711 West 17th Street, #F-6
Costa Mesa, CA 92627

Attention: Mr. Doug Haavik

Subject: Concrete Core Test Results
CTV Building Collapse Investigation
Project No. CT 15424.000

Gentlemen:

On April 27, CTL|Thompson (CTL) received from Dr. David Rothstein concrete cores identified as having been extracted from structural concrete members involved in the CTV Building Collapse Investigation. At the time of transfer of core segments from Dr. Rothstein, we discussed the scope of testing to be done by CTL| with Dr. Rothstein and Mr. Haavik. The attached data sheets present the test results from this laboratory study.

Description of Test Program

Eight concrete cores were transferred to CTL after they were visually logged in by Dr. Rothstein. Dr. Rothstein, Mr. Haavik and Mr. Werner determined the length of core which could be tested from each segment during the transfer and logging process. Mr. Werner transported the samples directly back to CTL's laboratory where sample preparation began.

ASTM test methods were used to test concrete core segments unless otherwise noted. Between April 27 and May 2, cores were kept in our laboratory with no intent to preserve their moisture condition. When the cores were transported, they were surface dry. On May 2, 2012, the core segments were cut to length perpendicular to the axes of the cores to create reasonably flat, nearly perpendicular ends. The cores were allowed to air dry overnight since the saw cutting was performed with water-cooled diamond-bit circular blades. The core segments were then measured for diameter and length, and they were weighed on May 3, 2012. Based on those measurements, the densities of the cores were computed. This information is presented in Table 1, attached. Olsen Engineering conducted pulse velocity testing on these cores in our laboratory on May 3. (CTL did not supervise that testing, and it was conducted independent of our studies.)

On May 7, smaller diameter cores (99 mm) were extracted from the as-received cores (145 mm diameter). This was necessary to obtain core segments free of cracks and with a sufficient length: diameter ratio to test them in compression. These cores were allowed to dry several hours, and then placed in waterproof bags in a temperature

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controlled room for until May 14, 2012. They were then tested for length, diameter and weight to determine their as-tested densities. The cores were then capped with sulfur capping compound to achieve a plane and essentially perpendicular surface on each end for compressive strength testing. After several hours, the cores were tested for compressive strength. Results of these tests are presented in Table No. 2. Please note fracture failures patterns were recorded and noted with the results. ASTM standards require this information for testing of concrete cylinders, but not for cores.

When the smaller cores were removed from the larger cores, annular segments were created. These annular segments were allowed to soak in water for 48 hours, at which time they were weighed in a submerged status and weighed in a saturated, surface-dry condition. After drying at 110C, the dry density and saturated surface-dry density of each of these pieces were computed and are presented in Table 3.

Segments created by sawing were labeled, saved and returned to Dr. Rothstein. Tested pieces were also returned to him.

Closure

The scope of services for CTL on this project was simply to perform these tests and report their results. Therefore no analysis of results is presented by CTL. The author is not licensed as a professional engineer in New Zealand, but the tests were conducted in our laboratory using standards put forth by the state of Colorado for the practice of engineering. CTL's laboratory is accredited through AASHTO (American Association of State Highway and Transportation Officials) to perform the work we have presented. CTL is regularly inspected by CCRL (Cement and Concrete Reference Laboratory), the last one having occurred in 2010, and the next scheduled for this year. CTL participates in the CCRL reference sample testing program for concrete as well as aggregates, cement, and pozzolans.

I have read the Code of Conduct for Expert Witnesses which BuddleFindlay provided, and it is my judgment the tests we conducted impartially provide data which can be used by the court and its experts to assess the quality and condition of concrete in the CTV Building as represented by the samples tested.

If you have any questions, please call.

Respectfully submitted,

CTL | THOMPSON MATERIALS ENGINEERS, INC.


Orville R. Werner II, P. E.
Principal



Enclosures

copies sent by email (willie.palmer@buddlefindlay.com; haavik86@gmail.com)

TABLE 1

REPORT OF DENSITY OF CONCRETE CORE SAMPLES
ASTM C 42, Standard Method for Obtaining and Testing Drilled Cores

Client: BuddleFindlay
Project: CTV Building Core Testing, Christchurch, New Zealand
Project No. CT15424.000
Placement Date: Circa 1986
Date cored: March 20-21, 2012
Date Tested: May 7, 2012

Report Date: May 23, 2012
Specified Strength (f'c): varies
Direction of Load with Respect to Placement: n/a
Nominal Maximum Aggregate Size: 19 mm
Method of Determining Density: Dimensional

Location of Cores:
Cores taken from site by others. As-received density only tested in this form.

Core ID	Weight (kg)	Height (mm)	Diameter (mm)	Density (kg/m ³)
C-1-T	5.95	157.2	143.5	2341
C-1-B	7.36	193.0	143.5	2358
C-4-T	5.68	144.0	143.5	2436
C-4-B	4.14	105.2	143.5	2431
C-7-T	7.41	191.8	143.5	2390
C-12-B	3.85	100.6	143.5	2368
R-3	7.05	189.0	143.5	2307
R-7	7.33	191.0	143.5	2374
			Average	2376

Notes: Cores were cut to length and allowed to surface dry. Weights and dimensions were measured.



TABLE 2

REPORT OF COMPRESSIVE STRENGTH TESTS OF CONCRETE CORE SAMPLES
ASTM C 42, Standard Method for Obtaining and Testing Drilled Cores

Client: BuddleFindlay
Project: CTV Building Core Testing, Christchurch, New Zealand
Project No. CT15424.000
Date cored: March 20-21, 2012 (in laboratory on 5/9/12)
Date Tested: 5/14/2012 - 5/16/2012

Report Date: May 23, 2012
Varies
Vertical
19 mm
Dimensional

Specified Strength (f_c):
Direction of Load with Respect to Placement:
Nominal Maximum Aggregate Size:
Method of Determining Density:

Location of Cores:
Cores taken from site by others. CTL extracted smaller cores to achieve visibly crack free samples with an appropriate L/D ratio.

Core ID	Age	Density (kg/m ³)	Height Capped, mm	Diameter (mm)	Area (mm ²)	Height/Dia Ratio	Correction Factor	Load (kN)	Fracture Type (ASTM C39)	Corrected Compressive Strength (MPa)
C-1-T	appx 25 yr.	2336	162.3	99.3	7747	1.63	0.970	259.3	2	32.5
C-1-B	appx 25 yr.	2358	198.9	99.3	7747	2.00	1.000	277.2	2	35.8
C-4-T	appx 25 yr.	2397	150.4	99.3	7747	1.51	0.961	565.0	2	70.1
C-4-B	appx 25 yr.	2416	112.0	99.3	7747	1.13	0.903	643.8	1	75.1
C-7-T	appx 25 yr.	2374	113.0	99.3	7747	1.14	0.905	259.4	2	30.3
C-12-B	appx 25 yr.	2357	108.5	99.3	7747	1.09	0.895	338.5	2	39.1
R-3	appx 25 yr.	2292	194.3	99.3	7747	1.96	1.000	220.2	2	28.4
R-7	appx 25 yr.	2356	196.9	99.3	7747	1.98	1.000	373.2	2	48.2
Average		2361						Average		40.0

Notes: A crack was discovered in C-7-T on 5/14, it was cut shorter to exclude the crack, and it was tested on 5/16/2012.

TABLE 3

REPORT OF DENSITY OF CONCRETE CORE SAMPLES
ASTM C 642, Standard Method for Density, Absorption, and Voids in Hardened Concrete

Client: BuddleFindlay
Project: CTV Building Core Testing, Christchurch, New Zealand
Project No. CT15424.000
Placement Date: Circa 1986
Date cored: March 20-21, 2012 (in laboratory on 5/7/12)
Date Tested: May 16, 2012

Report Date: May 23, 2012
Specified Strength (f'c): varies
Direction of Load with Respect to Placement: N/A
Nominal Maximum Aggregate Size: 19 mm
Method of Determining Density: Volumetric Displacement of water

Location of Cores:
Cores taken from site by others. CTL extracted smaller cores to achieve visibly crack-free samples. Densities were determined using annular remnants.

Core ID	Submerged Weight, kg	SSD Weight, kg	Dry Weight, kg	Soaked Density (kg/m3)	Dry Density (kg/m3)	Absorption, % by Soaking
C-1-T	1.524	2.631	2.512	2374	2267	4.7
C-1-B	1.930	3.309	3.148	2397	2280	5.1
C-4-T	1.540	2.610	2.535	2436	2365	3.0
C-4-B	1.091	1.853	1.799	2429	2358	3.0
C-7-T	1.910	3.257	3.112	2414	2307	4.6
C-12-B	1.012	1.735	1.665	2395	2298	4.2
R-3	1.821	3.180	3.027	2338	2225	5.0
R-7	1.869	3.214	3.101	2387	2303	3.6
Average	1.587	2.724	2.612	2396	2300	4.2

Notes: Concrete soaked in water at 23C for 48 hours.