CONCRETE MIX DESIGN COMPETITION: IMPLEMENTING CDIO IN CIVIL ENGINEERING.

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ABSTRACT

One of the challenges of incorporating design education into a Civil engineering curriculum is that of scale. Unlike electrical and mechanical courses where CDIO based curriculum can be applied to small electrical and/or mechanical devices, civil engineering focuses on design, construction and commissioning of large scale networks within the built environment, such as water treatment and distribution, wastewater management, transportation networks, etc. This paper will describe the incorporation of a concrete mix design competition within a senior year technical elective course at the University of Calgary. Students are given a terms of reference and then full access to the laboratory during a 13 week course, during which they must develop a mix design that best meets the specifications. Apart from learning laboratory skills (slump testing, air content, compression testing), the students gain an understanding of the challenges of quality control and assurance during production. The paper describes the evolution of the competition and outcomes as part of describing the effectiveness of this approach to a laboratory course in a traditional civil engineering curriculum.

KEYWORDS

Civil engineering, concrete mix design, CDIO syllabus 1.2, 2.2, 2.2, 2.5, 3.1, 3.2, 4.1, 4.4: CDIO Standards: 5 (Design-Implement Experiences), 7 (Integrated Learning Experiences), 8 (Active Learning)

INTRODUCTION

Like many programs in Civil Engineering students at the Schulich School of Engineering at the University of Calgary take a minimum of one core course in Civil Engineering materials that includes an introduction to cement and concrete. These two materials form the basis of much of the civil infrastructure and are the world's most commonly used materials exceeded only by petroleum products (Ashby 2014). The introductory curricula for concrete focuses mostly on the mechanical properties of the constitutive materials (aggregates and cement), laboratory and the field quality control and quality assurance tests needed to receive and accept the material at the job site. In secondary-level courses, the students learn more about the cement chemistry and variations to the most common concrete mixes (such as high strength concrete, high performance concrete, lightweight concrete, etc.). In 2001, a change was made to the Civil Engineering curriculum at the Schulich School of Engineering that resulted in development of a lab-based course that took the students deeper into the knowledge base of concrete mix design with the addition of a fourth year technical elective in concrete materials. The course has evolved since then, from focussing solely upon concrete mix design to one that is divided into two components: concrete mix design and structural design of reinforced concrete. Learning outcomes are defined for both halves of the course and the learning outcomes for the concrete mix component are as follows:

Part 1: *"Practical examination of concrete mix design (Portland cement), processes and systems to improve performance and sustainability of Civil Engineering structures."* At the end of this portion of the course, the students will be able to:

1. Develop a concrete mix design from experimentation,
2. Plan and execute experiments, while working independently in the fresh and hardened concrete laboratories, using appropriate instruments, careful data collection, and safe practices
3. Communicate the results of your work in a professional manner through a final report.

The course is timetabled as a three hour per week lecture with a three-hour laboratory session. Keeping in mind that an undergraduate course should be approximately 100 hours in length, the learning outcomes for part 1 are achieved through 100% laboratory work in the form of the "High Performance Concrete Competition (HPC)". With one introductory lecture, the students are presented with a fourteen page terms of reference for the competition that outline not only rules of the competition, but also describes the scoring process, penalties and bonuses, reference costs and materials sources (along with transportation costs) and the grading rubric for the final report along with a team peer evaluation form. As an added sweetener, there are monetary prizes as well.

HIGH PERFORMANCE CONCRETE COMPETITION

The competition focus has changed each year with students having to design high strength concrete, high performance concrete, self-compacting concrete, low-slump or high slump concrete, and/or concrete of a tightly specified strength. Regardless of the focus, the competition objectives have not changed and have been encapsulated in a quote from TaoTeh Ching 43 which is the opening statement of the HPC competition rules: *"The best instruction is not in words"*.

Specifically, the competition objectives are:

- To learn about optimum mix proportioning, casting, curing and testing techniques through the manufacture and testing of concrete specified for compressive strength, density, elastic modulus, economy and sustainability.
- To obtain more practice in written communication.
- To work efficiently as a team towards a common goal.
- To win the competition by obtaining the best sustainability score according to the formula given below.

The 2015 – 2016 competition required that students develop a concrete with a target compressive strength range of 35 +/- 3 Mpa, which is considered normal strength in Alberta, but the concrete was for a marine application in Vancouver, B.C. The mix had to have a slump of 100 mm. This somewhat sparse and cryptic specification required decoding as they had to research a) what normal strength concrete is in B.C. to first ascertain whether their concrete would be considered thusly and if not, what additional measures would be needed to make it so and, b) they had to research climate records to determine if frost protection is used/needed in the Vancouver application (it was not).

The competition is meant to be a learning experience and there is money on the line, but the final grade for this component of the course is based upon the final report, not the score in the competition. As students get deeper into the experience, this fact has to be repeated frequently as they forget that the journey (as reported in the final report) is the actual basis for their grade and not the final outcome in the form of a score.

Students self-select into groups of four and have to register their team and testing plan with the technical manager before they are given clearance to start work in the lab. Prior to that milestone, the very first thing they must do in order to start work is to develop their mix design philosophy: which requires research, debate and teamwork. The mix design philosophy was guided by their interpretation of the competition rules and scoring (for example, are they going to try and maximize the use of recycled material in their mix, or are they going for the best consistency between mixes…). Each team was allowed to make and cast three trial mixes prior to the competition casting day and with fixed competition casting and testing dates (October 28th and Nov 25th, respectively), the students had to work quickly in the first week to start their testing programs. Concrete compressive testing is done at 3, 7, 14, 21 and 28 days after casting which meant that within the bounds of a 12 week course that started on September 11th, most teams made their final mix design choice without one of the mixes having the full 28 day results to guide their final decision. Teams had to be registered with the lab tech by October 4th (three weeks into the term) and it was obvious to most students that the sooner they got busy, the better their chances of success would be. Registration with the Technical Manager (TM) required not only a full testing schedule (casting, demolding, grinding, compression testing etc.) but also a complete list of materials required to make their mixes and estimated quantities. Non-standard materials (such as recycled aggregate, rubber crumb, etc.) had to be supplied by the students and they could only be brought into the lab once a WHMIS/MSDS sheet had been supplied. Storage containers for non-standard material also had to be provided and students had to be ready to remove the material once the competition was over. Space was a limiting factor in some cases!

The Technical Manager(TM) responsible for the lab provided hands-on training for some of the equipment (for example, the compression testing and grinding machines) as well as overseeing all testing (fresh mix and hard concrete). Students were expected to do all lab tests/procedures on their own and the TM provided invaluable assistance to the students as a sounding board. While the students have a set three-hour lab session in their weekly schedule, they are in fact, given full and free use of the lab to develop their mixes, but all work has to be recorded/booked into a master schedule to avoid overcrowding. The maximum amount of time that can be booked at one time was one hour. This was to train them to work quickly as the final competition casting had to be done within a 30 minute window: teams that exceeded the 30 minute time limit on competition casting/testing days were assessed a time penalty. In addition, no work could be done after hours and students were required to work in teams for safety. Time and human resource management skills were required to fulfil the tight schedule which so students learned about teamwork on an operational level.

In the days prior to the competition-casting day, students were found to be discussing and arguing the merits of their designs, which, as a professor, was gratifying to overhear! Competition casting took place under the supervision of the Technical Manager and Teaching Assistant who certified the mix components on a ‘competition form’. Once cast, the concrete cylinders could be cured under various conditions to simulate real world production: fog room, ambient air, ambient water bath, or hot water bath, as well as combinations thereof. Each curing regime had an associated energy cost which had to be accounted for in the final scoring and economics.

After casting, students could test for compressive strength at 1,3,7, 14 and 21 days which allowed them to track how strength was gaining within their cylinders and make curing regime adjustments accordingly. For example, if the cylinders were in a hot water bath and were found to be gaining strength quickly, they could remove them from the bath and place them in to the cooler fog room. This adjustment would have a cost implication.

Scoring

The competition score was determined using the following equation:

$$Score = (S) - F_1 - F_2 - F_3 - F_4 - F_5 + F_6 - F_7 \qquad (1)$$

Where:

S		Is the mean compressive strength (MPa) for three cylinders successfully tested at 28 days during the competition compression testing. This must be between 32.00 and 37.99 MPa. Cylinders out of this range were rejected and a penalty applied to the Standard Deviation fctor as described below.
F_1	SD	Is a factor that applies a penalty or bonus to the standard deviation (MPa) of the compressive strength measurement on the three test cylinders. (If one or more test results are judged to be void as described above, then SD = 20 MPa).
F_2	D	The average density of the concrete, kg/m^3.
F_3	E	The elastic modulus (GPa). A penalty was applied to concrete that was excessively brittle.
F_4	AE	Accuracy of the estimated strength. Students had to estimate their final average strength prior to the competition compression testing that took place 28 days after competition casting. This factor was a very practical challenge for the students as in future clients will request a set strength and over delivering will have cost implications to the company and under-delivering will have design implications for the structural engineer who is counting on a fixed strength.
F_5	A	The air content (fresh concrete). This was the 'hidden' test for the students in 2015-2016 as the engineering of the air content is important for freeze-thaw protection, but inclusion of air-entraining agents has a cost associated and would not be used in the Vancouver marine environment.
F_6	C	The cost of the concrete in \$/m^3 and imposes a penalty or a bonus for economy of design based upon materials cost only (not including carbon content or energy costs). Teams using non-standard materials had to substantiate in writing the cost of any materials other than the stock materials supplied.
F_7	Co	Consistency, measured by the slump, which was set at 100mm. This factor is perennially the hardest specification to meet and in 2015-2016, the winning mix was the only one that met the slump target.

In addition to the score calculated above, students had to calculate the sustainability of their mix for one cubic metre of concrete using the following formula:

Sustainability Index = (Score * Energy (MJ/m^3)) / Emissions (kgCO2E/m^3))……….(2)

To calculate the cost in terms of dollars, energy and emissions for all the components as well as the available curing regimes students were given set values as shown in Table 2

Table 1: Delivered Costs, Energy and Emissions

Material	Cost CDN $ (delivered to F block SSE)	Total Energy MJ/tonne	kg CO_2E/tonne
Type 10 cement	$ 110 per tonne	8,030 (manufacturing)	1210
Type 30 cement	$ 130 per tonne	8,030 (manufacturing)	1210
Coarse and fine aggregate (virgin)	$ 9 per tonne	110 (mining, crushing)	8
Fly ash	$ 40 per tonne	-5 (capture)	-10 (scrubbin
Silica fume	$ 750 per tonne	-5 (capture)	- 8
Air entraining admixture (Micro-Air)	$1.45 per litre (avg. dosage 50-75 ml /100 kg cement)		15
Superplasticizer (Rheobuild 1000 / Glenium 3030))	$2.50 per litre (avg. dosage 500 ml/100 kg cement to double the slump).	115 (manufacturing)	200 (manufacturing)
Water		5 (WTP, WWTP, distribution)	
Ready-mix operations		205 (manufacturing)	19
Fly Ash Landfill Avoidance		-54	-18
Silica Fume Landfill Avoidance		-54	-18
Transportation - truck		2.54 / km	0.3 / km
Transportation - rail		0.41 / km	0.03 / km
Recycled C&D aggregate	To be supplied by student	80 (crushing)	7.9
Fog Room	0.50 /tonne /day	5.25/day	2
Waterbath – ambient	0.10 / tonne/day	5	
Waterbath – 30degC	0.75/ tonne/day	6	2
Waterbath – 50degC	1.00/tonne/day	6.2	2

All compression testing occurred exactly 28 days after the competition casting. All team members had to be present to reinforce the teamwork component of the competition. Results were reported during the compression testing and elastic modulus testing was completed by the Technical Manager over the following three days.

Reporting

All teams had to self-report their results using a standard spreadsheet to the professor and the results were revealed to the class on the final day of term. The spreadsheet not only checks the students' self-reported scores, but also calculates delta values to determine ‘closest to the pin’ values and standard deviation. Prizes (and prize money) was awarded in the following categories:

- Best Sustainability Score - $500
- Best Consistency (lowest standard deviation of three cylinders) - $100
- Closest to the required strength (35MPa) - $100
- Best Estimate - $100
- Best Slump (closest to the specification) - $100
- Highest use of recycled materials (on a volume basis) - $50
- Worst Sustainability - $25 (a consolation prize).

The HPC competition report forms 30% of the students’ grade and has proven to be an excellent way to not only involve them in the design process, but also to teach them valuable technical skills in the laboratory and field as well as operational teamwork skills. Students peer evaluate their teams to adjust their final grade according to the effort expended using a process described in Cowe Falls 2015.

OUTCOMES AND LESSONS LEARNED

Student feedback on the HPC has been very positive and comments have been clearly noted during the annual Universal Student Ratings of instructors (USRI) at the University of Calgary.

The success of the HPC is largely due to the support of not only the department of Civil Engineering, but also local industry suppliers, alumni who act as mentors to the students and the technical staff of the department. One of the greatest challenges is the number of students who are registering to take the course. In the first year, there were 32 students and that has doubled to 78 in 2015-2016. The result has been that when the competition first started, students were able to make five trial mixes prior to their competition mix and now with the limitations of time, the students only have time to make three mixes prior to the competition.

The most visible outcome of including the HPC in the Civil curriculum is the standing of the Universitie’s Great Northern Concrete Toboggan Team which began a steady run of podium finishes for the toboggan design as well as the technical component awards (best technical report, best use of fly ash, best mix design, etc.) after the initial offering of the course. This successful run for the team continues to this day.

I would like to especially note Dr. Robert Day who passed away suddenly in 2015. The HPC competition was his brainchild and hundreds of students have benefitted from his pedagogy and vision for this experiential learning course.

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BIOGRAPHICAL INFORMATION

Lynne Cowe Falls, PhD, P. Eng., FCAE, FCSCE, is an Associate Professor in Civil Engineering at the Schulich School of Engineering, the University of Calgary. She is a co-author of over 30 technical papers and several books in the area of pavement and infrastructure management and most recently of *Current Pavement Management.* With over 20 years in industry prior to joining the University of Calgary, she is a Vice-President and Board Member of the Transportation Association of Canada. Her recent research has focused on the effectiveness of leadership development programs in engineering curricula.

Robert Day, Ph.D. P.Eng (deceased) was a Professor in Civil Engineering at the Schulich School of Engineering, the University of Calgary. His area of research was in cement and concrete mixes and was the initiator of the High Performance Concrete Competition in 2001. He passed away in 2014.

Terry Quinn, is the Senior Technical Manager in Civil Engineering at the Schulich School of Engineering, the University of Calgary where he overseas the teaching and research laboratories and is directly involved in the materials labs in which the concrete competition occurs.

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