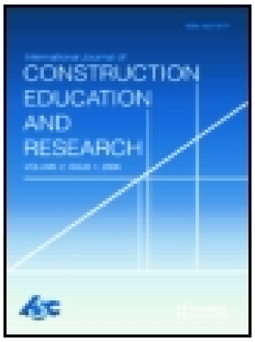

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ABSTRACT

A common method used to increase the strength of concrete is to add more cement to reduce the water-to-cement ratio. However, this is not always acceptable as adding more cement increases autogenous shrinkage, thermal and shrinkage cracking, and the cost of concrete production. By appropriately using superplasticizers, high-performance low cement concrete (LCC) can be produced. This study explores the potential of LCC by limiting cement content, adding alternative cementitious materials, and superplasticizers. Data was collected from the outcome of an annual National Student Concrete Competition conducted in Indonesia over three consecutive years. The new concept of LCC mix design was explained to all participants, i.e., civil engineering students, before they made their concrete specimens. Following the competition, all mixture compositions and their resulting concrete properties were analyzed. It was found that the participants' knowledge on the use of superplasticizer and cementitious materials was the most notable challenge. Nevertheless, they discovered that making LCC is a possibility. Concrete with a compressive strength of 50 MPa (7252 psi) can be made using cement content as low as 200 kg/m^3 (337 lb/yd^3) with sufficient workability. Furthermore, the effect of several factors on the performance LCC is described in this study.

KEYWORDS

Low cement; superplasticizer; fly ash; calcium carbonate; concrete competition; student competition

Introduction

Concrete, which is a major construction material, relies heavily on the use of cement to increase its compressive strength. This concept is slightly different from the basic principles of concrete mix design, where water content is manipulated to control workability; in other words, the water-to-cement ratio is varied to obtain the target strength. A high compressive strength can be obtained by lowering the water-to-cement ratio; however, in the construction industry, this means adding more cement rather than reducing water content. This condition is especially true in the Indonesian construction industry today and is an issue that needs to be addressed. The Indonesian Standard of concrete unit price for building and housing (Ministry of Public Works, 2007) shows that concrete with a target strength of 30 MPa (4351 psi) would normally need about 450 kg/m^3 (759 lb/yd^3) of cement. Ready-mix producers generally use a cement content similar to the standard, specifically 400 kg/m^3 (674 lb/yd^3) and 450 kg/m^3 (759 lb/yd^3) for concrete with a target

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strength of 35 MPa (5076 psi) and 40 MPa (5802 psi), respectively. These cement content levels in concrete can be considered excessive and result in high construction costs and increase environmental distress associated with cement production.

Low cement concrete mixture

The concept of low cement concrete (LCC) was introduced in 1987 (Naik & Ramme, 1987); it was proposed that good quality fly ash can be added to a concrete mixture to reduce its cement content and increase compressive strength. Other researchers also proposed similar concrete mixtures (Huang, Lin, Chang, & Chen, 2013; Kubissa, Simon, Jaskulski, Reiterman, & Supera, 2017; Rashad, 2015; Ravina & Mehta, 1988). Apart from the addition of cementitious materials to replace cement, LCCs can also benefit from the optimization of aggregate content. Phelan (2004) introduced the term "athletic concrete" in which lean concrete achieved a high compressive strength upon optimizing aggregate gradation and using supplementary cementitious materials. Optimization of the mix design to reduce cement content was also investigated (Dewar, 2000; Jiao, Shi, Yuan, An, & Liu, 2018; Su & Miao, 2003) and different methods were employed to achieve high-performance concrete with the lowest possible cement content.

The basic principle of LCC mix proportion proposed in this study is to incorporate the lowest cement content in concrete using a cementitious material to increase the paste content and employ a superplasticizer to reduce water content to achieve a low water-to-cement ratio. The properties of both fresh and hardened concrete can be controlled separately.

The reduction in cement content needs to be balanced with the addition of fine particles (e.g., cementitious material or fine powder) to concrete to increase segregation resistance and cohesion (Lothenbach, Scrivener, & Hooton, 2011; Schöler et al., 2017; Shannag, 2000). The addition of fly ash can reduce water content in the mixture due to the spherical particle shape of fly ash (Antoni, Widianto, Wiranegara, & Hardjito, 2017; Berryman, Jensen, & Zhu, 2006; Huang et al., 2013; Rashad, 2015; Ravina & Mehta, 1988). Other supplementary materials, such as pozzolan or limestone powders, can be added as fine materials to the mixture (Bonavetti, Donza, Menéndez, Cabrera, & Irassar, 2003; Díaz et al., 2017; Lothenbach, Le Saout, Gallucci, & Scrivener, 2008).

Water content in concrete can be reduced using a superplasticizer to increase the strength of the paste as the cement content is reduced. A superplasticizer is also necessary when powder content in the concrete mixture is increased. Polycarboxylate-based superplasticizers are often recommended as they exhibit good stability when used in concrete (Antoni, Halim, Kusuma, & Hardjito, 2017; Huang et al., 2016; Liu et al., 2017; Tan et al., 2017; Toledano-Prados, Lorenzo-Pesqueira, González-Fonteboa, & Seara-Paz, 2013; Yoon & Kim, 2018).

The workability of a mixture can be controlled by changing the paste-to-aggregate ratio (Jones, Zheng, & Newlands, 2002). The basic principle of proportioning fine aggregate and coarse aggregate is similar to proportioning in normal concrete to obtain the maximum aggregate volume in the mixture. The paste-to-aggregate volume ratio needs to be increased when a high workability is required.

The above-described points make it clear that the usage of LCC needs to be explored further as it can potentially result in huge economic savings for the construction industry. Furthermore, LCC is an environmentally friendly construction material as it employs fewer natural resources and offers several opportunities to utilize waste materials.

Student concrete competition

Lomba Kuat Tekan Beton (LKTB) or the National Student Concrete Competition is an annual competition organized by the Civil Engineering Student Association of Petra Christian University, Surabaya, Indonesia since 1991. For the past 10 years, green concrete has been the main theme of the competition, the aim of which is to produce sustainable concrete materials by optimizing material proportions and selection. Previous competitions with themes such as Porous Concrete (Antoni, 2009), High Volume Fly Ash Concrete, and Geopolymer Concrete were also held. LKTB has gained national popularity among civil engineering students, who come from various universities throughout Indonesia to participate in the competition.

The competition aims to broaden students' knowledge on current trends in concrete technology by focusing on a particular theme. In the context of the competition, the students' goal is clearly set and their learning outcomes can be readily evaluated (Bigelow, Glick, & Aragon, 2013; Hamid, Baharom, Taha, & Kadaruddin, 2013). In this competition, learning outcomes were evaluated by analyzing concrete properties made by the participants. The use of low cement content was imposed as a constraint in the competition and participants were required to produce concrete with the highest possible compressive strength.

In this study, we discuss the results of the competition and highlight possibilities and challenges involved in applying the new LCC mix design concept. The results of the competition provide insight into the knowledge possessed by civil engineering students on LCC. Likewise, data on mix proportions and the resulting properties (fresh and hardened mixes) would be useful as a guide in producing high-performance low cement concrete.

Methods and materials

The main theme of the competition from 2016 to 2018 was "Low Cement Concrete," in which participants were challenged to produce a concrete mixture with a limited cement content. The cement content was limited to 275 kg/m^3 (464 lb/yd^3), 250 kg/m^3 (421 lb/yd^3), and 200 kg/m^3 (337 lb/yd^3) in 2016, 2017, and 2018, respectively. Cementitious material was added to ensure that there was enough paste in the mixture and to foster an understanding of its usage. The limitation was imposed to challenge participants' knowledge and to show that there are other methods to produce good quality concrete apart from adding more cement. Making concrete with the highest achievable strength with moderate workability and limited cement content was the goal of every team, which consisted of 2–3 civil engineering students, with merit points given for cost saving mixtures.

Methods

The LCC concept was introduced and described to the participants at the beginning of the competition by the first author. The participants were also supplied with the data and results of the previous year's competition. Lessons learned from the previous year were also highlighted. Each team, consisting of two or three undergraduate civil engineering students from the same university, was required to participate for two days to attend the lecture on LCC, determine their LCC mix composition, and cast two concrete cylinders with a diameter of 15 cm (6 in) and height of 30 cm (12 in).

At the time of mixing, all teams were provided with materials required for making their concrete samples. The mixture proportion of the materials was determined by each team after considering the results of the previous year's competition and taking the limitation imposed in the competition into consideration. All the participants mixed their concrete manually at the same time. This was ensured to avoid variation in materials and equipment and to keep the competition fair and lively. Tests on fresh concrete properties, such as slump and wet density, were conducted on the mixing day. Concrete specimens were cured by water immersion for 27 days after which their compressive strength was tested on the 28th day. Ten teams with the highest number of points were selected for the final round, in which they made presentations and were judged based on their knowledge.

The target slump value for the 2016 competition was set at (10 ± 2) cm ((4 ± 0.75) in) to simulate proper target workability and facilitate hand compaction. It was soon realized by the authors that the target workability was not necessarily accurate as the upper bound of a slump of 12 cm (4.75 in) is not necessary. Concrete mixtures with higher workability can still perform well; it was actually difficult and unnecessary to maintain a narrow workability range as good workability can be achieved by the addition of a superplasticizer. The target slumps for 2017 and 2018 were revised to a minimum of 8 cm (3 in) with no maximum value. Concrete mixtures could have high slumps up to 30 cm (12 in) or slump flow as long as the concrete did not exhibit a segregation tendency. Segregation was defined as the separation of paste and aggregate when measuring slump. It was also observed when water separated from the concrete mix immediately after stopping the mixing action. Figure 1 compares a proper mixture without segregation and a segregated mixture. The former was unified uniformly with aggregates at a high slump value, while in the latter, water and aggregate separated.

The 28-day strength target was set as high as possible with no lower limit. Each team also needed to gain points in terms of the uniformity of two sample specimens and optimization of the mixture composition, with merit points being given to teams who used a low cement content. The number of participants in the concrete competition is shown in Table 1. Some were disqualified due to their inability to make two complete specimens; their specimens disintegrated when curing or there was a miscalculation in the mix design. The percentage of disqualified teams reduced across each year. This showed that our attempt to increase the knowledge of the participants by presenting the previous year's results was effective.

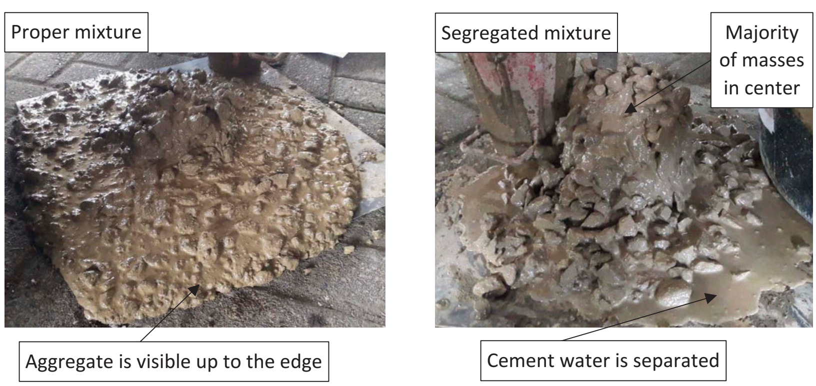

Figure 1. Example of the proper and segregated mixture of the fresh concrete.

Table 1. Concrete competition participants and valid data gathered.

	2016	2017	2018
Participants (teams)	90	75	60
Disqualified participants (%)	18 (20%)	13 (17%)	5 (8%)
Valid data	72	62	55

Every team had to prepare and mix concrete manually in a plastic bucket (Figure 2), all materials given to the participants were specific to the mix design submitted, and the sequence of mixing was conducted in line with the teams' preferences. The workability and wet density of the specimens were tested on site. The specimens were then cured in a mold overnight and demolded the next day. Compressive strength tests were conducted by a laboratory technician on the 28th day from the mixing day.

Data on the mixture proportion and properties obtained during the competition were tabulated and analyzed. Such analysis on data acquired over 3 years was aimed at determining the upper bound values of the properties of fresh and hardened concrete and their correlation with the water-to-cement and water-to-cementitious material ratios, cement and cementitious material content, and superplasticizer dosage. The maximum achievable concrete strength at a limited cement content was evaluated from the upper bound values, which represent the potential strength of the LCC produced, while disregarding low-quality specimens. The large variation in results can be attributed to variations in the concrete-making skill of the participants rather than to variations in the chosen mixture composition. Hence, unlike upper bound values that show the potential strength of concrete at low cement contents, average values do not have a significant meaning.

Materials

The materials distributed to participants are listed in Table 2; they were obtained from several sponsors in the construction industry. Each team could choose between two coarse crushed stone aggregates, 5–12.5 mm (0.25–0.5 in) and 12.5–25 mm (0.5–1 in). Sand taken from a local quarry in Lumajang, East Java, Indonesia, was provided. The fineness modulus (FM) and specific gravity (GS) of these materials are also listed in the table. Fly ash was sourced

Figure 2. Concrete competition in progress, manual mixing, slump testing and the specimens made.

Table 2. Materials provided for the competitions and its specifications.

Material Used	2016	2017	2018
Cement	Portland Composite Cement, Tiga Roda	Ordinary Portland Cement, SCG cement	Ordinary Portland Cement, SCG cement
Sand	Lumajang quarry, East Java, Indonesia FM = 2.97, GS = 2.72	Lumajang, FM = 2.22, GS = 2.72	Lumajang, FM = 2.45, GS = 2.70
Crushed Stone			
5–12.5 mm	FM = 6.36, GS = 2.46	FM = 6.10, GS = 2.63	FM = 6.19, GS = 2.63
12.5–25 mm	FM = 7.56, GS = 2.66	FM = 7.62, GS = 2.73	FM = 7.74, GS = 2.73
Fly ash	Source: Paiton Powerplant, East Java, Indonesia, High Calcium (Class C), GS = 2.63		
Calcium Carbonate	passing #200 (48 μm), GS = 2.70	-	passing #100 (75 μm), GS = 2.70
Silica fume	>85% SiO_2, GS = 2.2	-	-
Superplasticizer	Type: PCE	Type: PCE	Type: PCE

from a pulverized coal combustion power plant in Paiton, East Java, Indonesia and it was categorized as high-calcium fly ash or class C fly ash. A report on this grade of fly ash was also provided to the participants (Antoni, Widianto et al., 2017). The cementitious material was selected to conform to the theme of the competition. In 2016, fly ash, calcium carbonate, and silica fume were offered to the participants; however, the use of too many cementitious materials seemed to confuse the participants and no team could achieve a strength comparable to that usually achieved with silica fume (Antoni, Chandra, & Hardjito, 2015; Shannag, 2000). In 2017, only fly ash was offered as the cementitious material and in 2018, calcium carbonate-added fly ash was provided as the cementitious material. Calcium carbonate was found to increase the early strength of concrete and hence may be advantageous in the mixture (Díaz et al., 2017). The chemical admixture provided was a polycarboxylate ether (PCE)-based superplasticizer available in the market (Antoni, Halim et al., 2017). All materials were provided to the participants on the mixing day to reduce the effect of material variation on compressive strength.

Results and discussion

Mixture compositions received from the participants and the corresponding compressive strengths were analyzed to evaluate the strength achievable with the lowest cement content in the mixture. Records were not maintained on water content and superplasticizer in 2016 and hence the above-mentioned parameters could only be analyzed with the data corresponding to 2017 and 2018. An overall trend could be observed in the mixture compositions and the resulting properties. The behavior and properties of fresh and hardened LCC are discussed in the following section.

Properties of fresh concrete

Various factors affect the workability of concrete mixtures. In the case of a conventional mixture, some of the more prominent factors are the water content in the mixture, cement and cementitious material content and their physical properties, and aggregate grading, proportion, size distribution, and its physical properties, such as shape and texture. Other external factors, such as temperature and environmental humidity, also influence the properties of concrete.

When a superplasticizer is used, workability of the mixture becomes dependent on the viscosity and volume of paste in the mixture rather than on the water content (Antoni, Halim et al., 2017). Viscosity of a concrete mixture can be controlled using a superplasticizer and by adding cementitious or other fine grain materials. The ratio of water-to-cementitious material content can be manipulated to control the viscosity of a mixture. Other additives, such as viscosity modifying agents, can be used to control the viscosity of the mixture when fine particle content is limited. However, it was considered that the addition of more admixtures would just confuse the participants.

The results of the competition showed that there was a broad variation in the slump value with respect to cementitious material content and water-to-cementitious material ratio as shown in Figure 3. It was observed that the slump value increased with an increase in cementitious material content (Figure 3a), but the increase in workability was mainly attributed to an increase in the paste content of the mixture and viscosity control.

Water content in the mixture also plays an important role in determining the properties of the mixture, as there is a minimum water content required to achieve a workable mixture, regardless of the workability needed. Too little water would result in a harsh mixture and even mixing cannot be achieved if the superplasticizer dosage is greater than the recommended level. Figure 3c shows that the required water content was about 125 kg/m^3 (211 lb/yd^3) to achieve a good workability, while some concrete mixtures could have water contents as low as 100 kg/m^3 (169 lb/yd^3).

The commonly practiced requirement of having a small targeted slump range to ensure homogeneity and consistency in the mixture is no longer necessary. Instead, with the use of a superplasticizer, minimum slump and absence of segregation should become the new acceptance criteria. A higher or lower slump than the target value would indicate that there was some inconsistency in the mixture proportion or the material. When a superplasticizer is used, these factors are no longer relevant, as the workability of concrete can be manipulated across a broad range by changing the superplasticizer dosage. Another important factor to be considered is mixture segregation, where water would simply flow out from the mixture and leave the aggregate, thus resulting in an inhomogeneous concrete mix. Controlling the viscosity of the mixture was found to be more important than controlling the slump value. Finally, the two most important requirements for workable concrete mixes were deemed to be a minimum slump value and preventing segregation.

The influence of superplasticizer dosage on the slump value of concrete is illustrated in Figure 3d. Slump increased with an increase in superplasticizer dosage; however, the broad range of dosage and slump also indicates that it was not the only factor controlling the behavior of fresh concrete. Further, it was observed that slump decreased at high superplasticizer dosages, which indicates segregation in the mixture. With some mixtures, there was almost zero slump at a high superplasticizer dosage, which indicates complete segregation. The ability of the participants to use the admixture properly is proven by the large variations observed in the results. It seems that some participants did not know how to calculate and use the superplasticizer in the concrete mixture at all.

Water-to-cementitious material ratio, water content, and superplasticizer dosage did not affect slump as separate factors; instead, they were correlated with each other. Therefore, it is suggested to employ viscosity and the volume of paste in the mixture as controlling parameters to manipulate workability. It was also observed that workability increased with an increase in

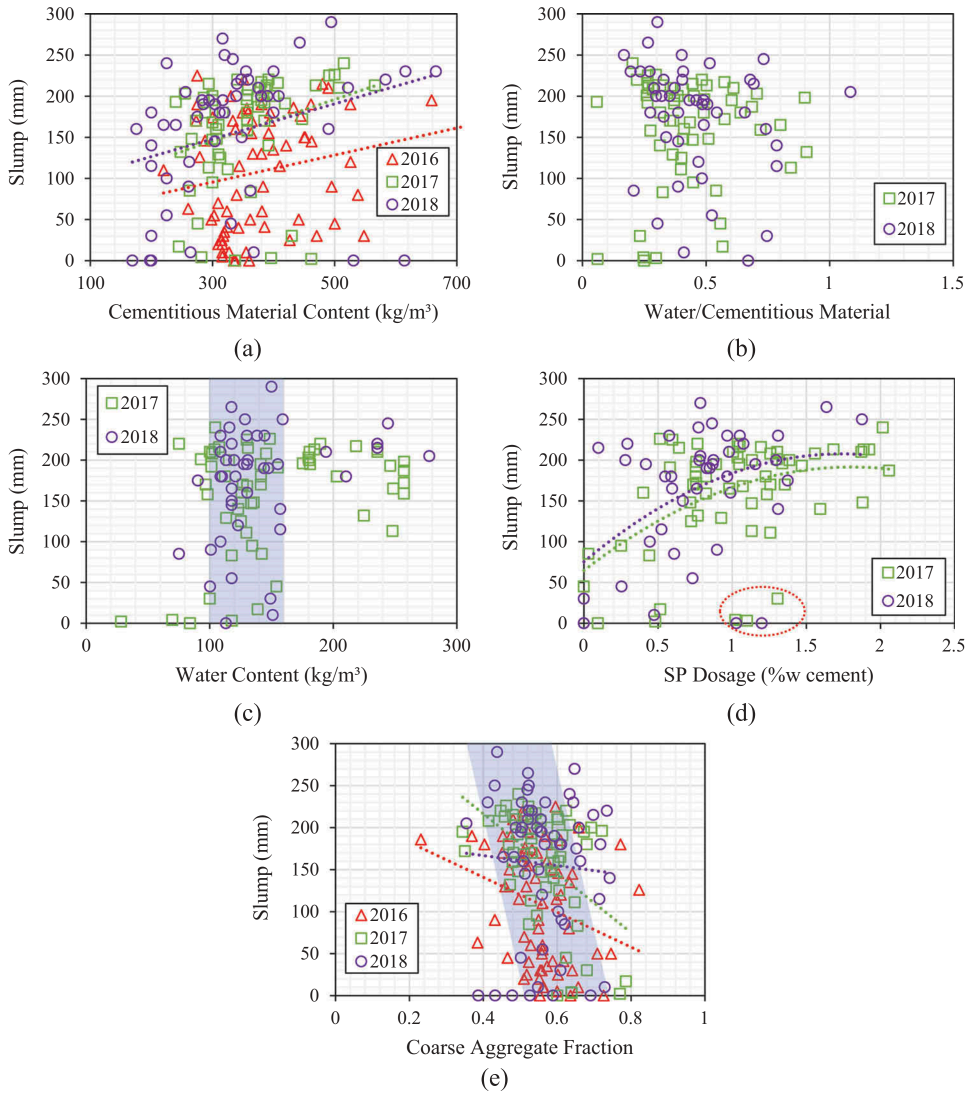

Figure 3. Slump value of the concrete mixture in correlation to (a) cementitious material content, (b) ratio of water-to-cementitious material, (c) water content, (d) superplasticizer dosage at a percentage to the cement content, and (e) coarse aggregate fraction.

slump. However, too much superplasticizer would also cause segregation as water would be freed into the mixture and reduce the overall mixture viscosity (Figure 3d).

Figure 3e shows that there exists an inverse relationship between slump and the coarse aggregate fraction in a concrete mix. Reducing coarse aggregate content in the mixture to increase the workability of concrete is similar to the concept of self-compacting concrete. The results show that at a coarse aggregate fraction of 0.5 to 0.6, a concrete mix exhibits high workability. Coarse aggregate fraction can be thought of as the inverse of cementitious material content. Upon increasing cementitious material content in a concrete matrix, the fine and coarse aggregate fraction reduced and workability increased.

Properties of hardened concrete

The properties of hardened concrete, which are usually represented by the compressive strength of the concrete, are controlled by the amount of cement in the mixture (Figure 4a). A large cement content results in a high compressive strength. However, this was not the case according to the data acquired in the competitions conducted in 2016, 2017 and 2018. The data acquired over these three years indicated that the maximum achievable strength increased with an increase in cement and cementitious material content (Figure 4b). However, the rate of increase gradually reduced and beyond a certain point, strength does not increase any more. The upper limit of achievable compressive strength can be seen in Figure 4a,b; however, a better understanding may be achieved by further reducing the cement content. The optimum cement and cementitious material content in a concrete mixture was observed to be about 250 kg/m^3 (421 lb/yd^3) and 400 kg/m^3 (674 lb/yd^3), respectively. Further addition of these materials did not increase the compressive strength anymore. Addition of more cement would only increase the cost of the mixture without any beneficial changes in concrete strength; it may also adversely affect the properties of hardened properties by inducing shrinkage and cracking.

Meanwhile, the addition of cementitious material to the mixture is deemed beneficial as it increases mixture consistency, segregation resistance, and reduces shrinkage. In the competition, good quality fly ash, calcium carbonate, and silica fume were used as cementitious materials.

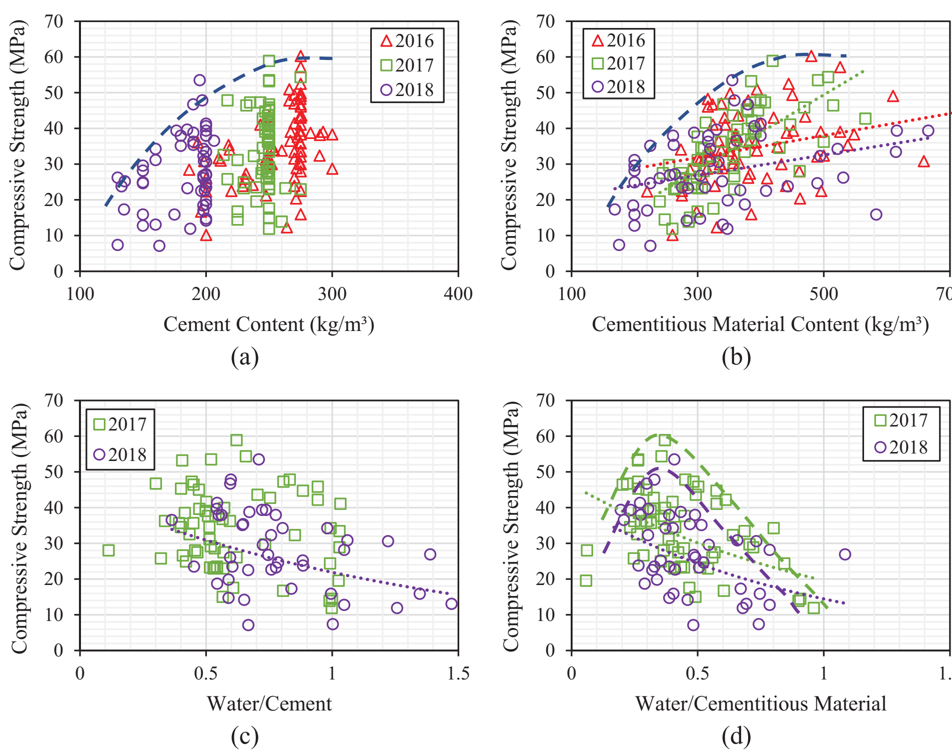

Figure 4. Concrete compressive strength correlation to (a) cement content, (b) cementitious material content, (c) ratio of water-to-cement, and (d) ratio of water-to-cementitious material.

Compressive strength was influenced significantly by the water-to-cement ratio (Figure 4c), or in this scenario, by the water-to-cementitious material ratio (Figure 4d), rather than by the cement or cementitious material content. Reducing the water-to-cementitious material ratio increased the compressive strength of concrete. However, reduction in this ratio beyond a certain extent made the mixture unworkable; such mixes could not be compacted into solid concrete, which adversely affected their compressive strength. A water-to-cementitious material ratio of 0.26 to 0.4 resulted in a compressive strength greater than 50 MPa (7252 psi) as shown in Figure 4d, under hand mixing and manual compaction conditions. Moreover, the water-to-cement ratio has a poor correlation with compressive strength, and hence, should not be used to determine target strength when using cementitious materials in the mixture. MacDonald (2014) stated that the water-to-cement ratio should be kept greater than 0.3 to avoid autogenous shrinkage. However, this ratio can be reduced when cementitious materials are used in the mixture. The percentage replacement of cementitious material in the mixture still needs to be considered as a high replacement ratio would reduce the final strength of concrete.

The correlation between properties of fresh and hardened concrete is shown in Figure 5. Slump and compressive strength did not display any significant correlation, which indicates that these two properties are independent of each other. Using a superplasticizer in the mixture would increase slump without any degradation in the strength of the concrete. The traditional method of increasing water content to achieve a high slump, which would result in a reduction in compressive strength, was no longer applied. The maximum strength values of concrete with a slump value of ~200 mm (8 in) developed during the competition (2016–2018) are highlighted.

Concrete with good workability and high strength is currently being employed as self-compacting concrete, but the traditional method of using water to control mixture workability is still being widely practiced. Usually, to increase concrete strength, more cement is added to the mixture. In future, these practices should be replaced by the use of admixtures, such as superplasticizers, to control the properties of fresh and hardened concrete.

The bulk density of concrete exhibits a significant correlation with its compressive strength; a dense specimen with few voids and pores exhibits a high compressive strength. However, bulk density is influenced by the density of the aggregate, which occupies the largest volume in the concrete mix. Variation in the bulk density of concrete produced using the same aggregate reflects variations in mixture compaction.

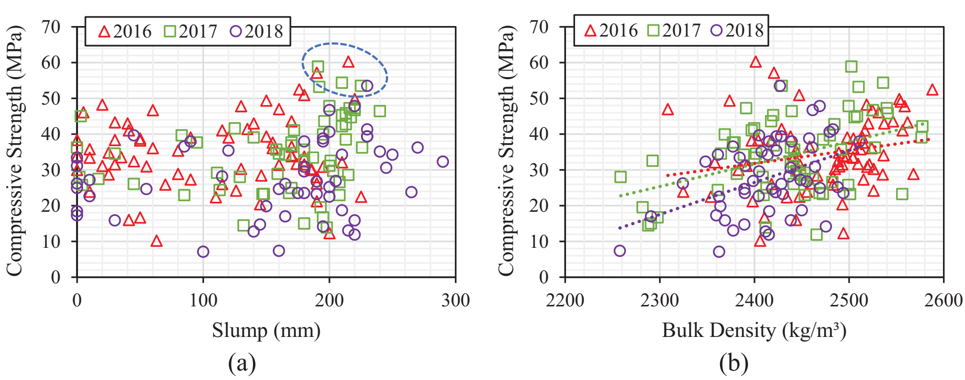

Figure 5. Concrete compressive strength correlation to (a) slump value, and (b) bulk density of concrete specimens.

Role of the superplasticizer

The dosage of a superplasticizer used to change the workability of fresh concrete does not exhibit a significant correlation with its compressive strength. Figure 6 shows the compressive strength achieved with cement and cementitious material superplasticizers at different dosages. The data points were significantly scattered and no specific trend could be observed. Thus, it is essential to reiterate that superplasticizer usage helps to mainly control the behavior of fresh concrete but it has no direct correlation with the properties of hardened concrete (Figure 3d). However, there is strong evidence that a high strength can be achieved only when a superplasticizer is added to the mixture. The optimum dosage necessary was about 0.4 mass% to 1 mass% for cement and about 0.4 mass% to 0.6 mass% for cementitious materials. Determining the optimum superplasticizer dosage in relation to cement or cementitious material content still needs further experimentation as different cementitious materials have different effects.

Cementitious material in concrete

The compositions of cementitious materials designed by the top ten teams who achieved the highest concrete strength over three consecutive competition years are shown in Figure 7. It can be observed from the figure that a high cementitious material content does not necessarily correlate with a high strength. A cementitious material content of 300 kg/m^3 (506 lb/yd^3) to 400 kg/m^3 (674 lb/yd^3) is sufficient for obtaining good quality concrete with proper workability and compressive strength.

The cementitious materials used in our competitions were cement, fly ash, silica fume, and calcium carbonate powder. It should be noted that different cementitious materials have different beneficial or detrimental effects on the properties of fresh and hardened concrete. Fly ash, which is generally thought to be beneficial in fresh concrete due to its spherical shape, varies in its quality and hence its effect needs to be tested continuously. The role of calcium carbonate in concrete mixtures needs to be studied further because there is a possibility of it increasing the early-age strength of concrete (Lothenbach et al., 2008).

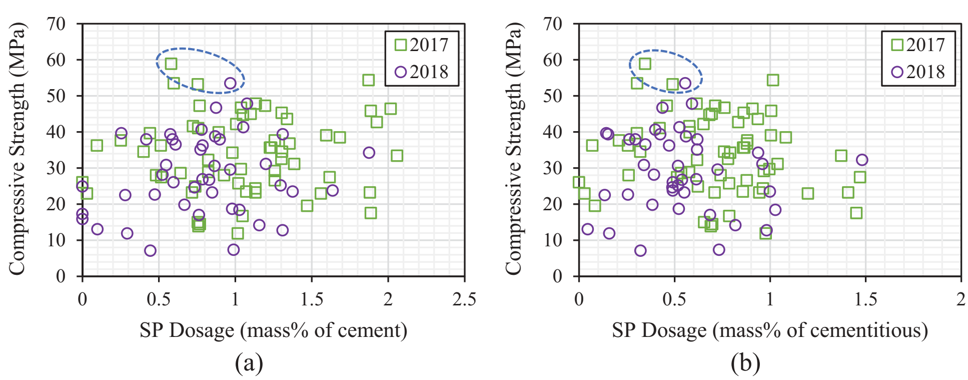

Figure 6. Concrete compressive strength correlation to superplasticizer dosage measured by percentage to (a) cement content, and (b) cementitious material content.

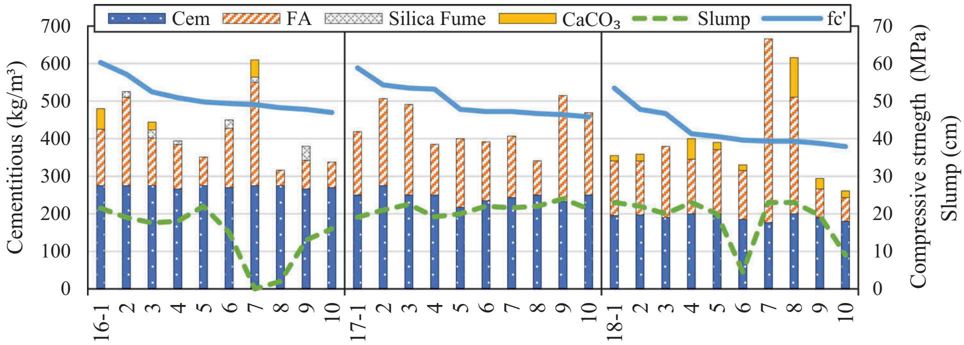

Figure 7. Detail of cementitious material used by teams with top ten strength.

Concrete with a target strength greater than 80 MPa (11603 psi) would benefit from the use of silica fume as it can fill micropores and increase compressive strength. In lower strength mixtures, it can increase cohesion without increasing strength; however, the high cost of silica fume and superplasticizer dosage should be kept in mind. Thus, after the first year, silica fume was not used in the competition anymore. The use of silica fume in the construction industry should also be evaluated as most concrete structures using silica fume can achieve a compressive strength of only about 50 to 60 MPa (7252 to 8702 psi), thus increasing construction cost without any increase in the compressive strength.

The overall compressive strength results from the competition are shown in Figure 8. Over the years, cement content was reduced from 275 kg/m^3 (464 lb/yd^3) to 200 kg/m^3 (337 lb/yd^3) without limiting the cementitious material content. The resulting maximum strength was reduced from 60 MPa (8702 psi) in 2016 to 58 MPa (8412 psi) in 2017 and 53 MPa (7687 psi) in 2018. The average strength also reduced with a reduction in cement content. However, one important issue here is that the cement content used in normal concrete mixtures is much greater than that used in the competition, even for low target strengths. Cement content used in the ready-mix industry is about 350 kg/m^3 (590 lb/yd^3) for a target strength of 30 MPa (4351 psi) and it can be increased to 500 kg/m^3 (843 lb/yd^3) for a higher target strength. Such concrete mixtures with high cement content of more than 350 kg/m^3 (590 lb/yd^3) can benefit by replacing cement with cementitious materials; however, such replacement should be carried out with great control. LCC has the potential to reduce the cost per cubic meter of a concrete structure; however, adding superplasticizer and cementitious material increases construction cost. Hence, several alternative mix proportions should be designed for maximum savings.

The results obtained from the competition show that the participating students were capable of making LCC using their knowledge. They gained practical experience during the competition, which combined technical and non-technical aspects that simulate real-world processes (Wankat, 2005). Initially, at the beginning of the competition, several students expressed doubts on the capability of LCC to produce high-strength structures. However, it was observed over several years that during the course of the competition, participants realized that it is indeed possible to produce high-strength concrete at low cement contents. Several students opined that participating in the competition increased their technical knowledge, communication skills, and teamwork capacity.

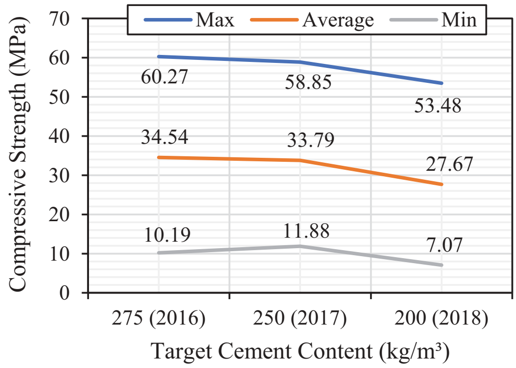

Figure 8. Concrete compressive strength achieved with the target cement content in the mixture.

Some variations and uncertainties in material properties, lack of knowledge on cementitious material behavior and superplasticizer, the newly introduced concept of LCC mix design, poor teamwork during designing, making and casting LCC, and even unfriendly weather conditions were some of the challenges faced by all the participants. These challenges also represent some of the hurdles that need to be overcome for the successful application of LCC in the construction industry.

Conclusions

The results of the LKTB national student concrete competition (2016–2018) show that high-performance LCC can be produced even under imperfect mixing conditions and with considerable variations in the participants' technical ability. A low cement content in concrete mixture yielded concrete with excellent properties and hence should be explored further for real applications in the concrete industry.

The major conclusions of this study are as follows:

- LCC can be a good solution to reducing cement content without reducing concrete performance. It can be manufactured with low cement contents by the addition of cementitious materials and controlling the water content of the mixture using a superplasticizer. This method produces concrete with excellent fresh and hardened properties that can conform to construction demands.
- Significant changes that occur in concrete mix design when cementitious materials and superplasticizers need to be addressed. The common mix design, based on water content to control workability and water-to-cement ratio to control compressive strength, becomes irrelevant when superplasticizers are used.
- Information on the behavior of concrete mixes produced with superplasticizers needs to be widely disseminated so that LCC can be further accepted. Concrete makers should revisit their understanding of the conventional correlation between slump and workability as a low slump range is not relevant when using superplasticizers to control the rheology of concrete.
- There were significant differences in the participants' knowledge on the use of admixtures and supplementary cementitious materials. Therefore, more effort is required to introduce the new LCC mix design concept as it is based on the inclusion of two or more materials in the mix design.

- Student concrete competitions are excellent opportunities to introduce new LCC mix design concepts and to show their possible applications and highlight challenges that need to be addressed for the wide-spread use of this new technology in concrete and construction industries.
- The high-performance LCC produced in this competition is limited by the quality of the materials used. Comprehensive information should be obtained when using different types of materials with differences in quality.

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