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A Comparative Analysis of Mix Proportioning for Prescriptive and Performance-Based Specifications for Sustainability

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Abstract

With the recent advancements in concrete technology, design and production of "green concrete" is increasing in demand. Although, the production of structures that are entirely sustainable is still challenging, industry has shown progress by motivating alternative solutions to conventional concrete such as using recycled aggregates, binary and ternary mixes with high levels of supplementary cementitious materials, and alternative binders with different chemistry with lower carbon footprints than portland cement. However, mix proportioning guidelines for performance-based specifications have fallen behind these advancements. ACI 211, the mostcommonly used mix proportioning guideline for prescriptive-based specifications, is primarily focused on structural concrete, and has not been updated after the recent developments in concrete technology. ACI 211 is conservative in recommending the cementitious materials content which negatively impacts sustainability, despite the well known relation between cement production and carbon dioxide emissions.

This paper addresses the effect of mix proportioning on sustainability by comparing the corresponding carbon footprint of cementitious materials required when proportioned based on ACI 211 mix proportioning guidelines and performance requirements for concrete pavements. The performance criteria for concrete pavements were selected, and the quantity of materials was calculated following the ACI 211 mix proportioning guidelines to achieve the desired workability and strength. Sixty different binary and ternary mixes were proportioned based on performance requirements which were verified by testing fresh and hardened properties. The comparison between the calculated cementitious materials content recommended by ACI 211 with the required cementitious materials content of performance-based mixes to achieve the same given performance criteria, as well as their associated carbon footprints are presented and discussed.

Disciplines

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Comments

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A COMPARATIVE ANALYSIS OF MIX PROPORTIONING FOR PRESCRIPTIVE AND PERFORMANCE-BASED SPECIFICATIONS FOR SUSTAINABILITY

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Abstract

With the recent advancements in concrete technology, design and production of “green concrete” is increasing in demand. Although, the production of structures that are entirely sustainable is still challenging, industry has shown progress by motivating alternative solutions to conventional concrete such as using recycled aggregates, binary and ternary mixes with high levels of supplementary cementitious materials, and alternative binders with different chemistry with lower carbon footprints than portland cement. However, mix proportioning guidelines for performance-based specifications have fallen behind these advancements. ACI 211, the most commonly used mix proportioning guideline for prescriptive-based specifications, is primarily focused on structural concrete, and has not been updated after the recent developments in concrete technology. ACI 211 is conservative in recommending the cementitious materials content which negatively impacts sustainability, despite the well known relation between cement production and carbon dioxide emissions.

This paper addresses the effect of mix proportioning on sustainability by comparing the corresponding carbon footprint of cementitious materials required when proportioned based on ACI 211 mix proportioning guidelines and performance requirements for concrete pavements. The performance criteria for concrete pavements were selected, and the quantity of materials was calculated following the ACI 211 mix proportioning guidelines to achieve the desired workability and strength. Sixty different binary and ternary mixes were proportioned based on performance requirements which were verified by testing fresh and hardened properties. The comparison between the calculated cementitious materials content recommended by ACI 211 with the required cementitious materials content of performance-based mixes to achieve the same given performance criteria, as well as their associated carbon footprints are presented and discussed.

Introduction

Concrete has been reported to be the second most widely consumed material by human beings (Flower and Sanjayan 2007). Given that concrete is ranked right after water, which is vital to the survival of every living organism on Earth, the importance of concrete in people’s lives is even more remarkable. As the world's population rapidly increases, the demand for rapid urbanization has grown in parallel. Fortunately, the concrete construction industry has (largely) met the need for housing in a timely manner in the developed world (Mehta and Burrows 2001). However, once scientists started informing the public about global warming and the impact of human activities on the environment, concern regarding the carbon footprint of cement production has been raised. Simultaneously, design and production of "green concrete" has come to be in greater demand. Hence, with the recent advancements in concrete technology, it has became a priority for the concrete industry to replace the long-known traditional "grey" concrete with "green" concrete, which is more environmentally-friendly.

Although, the production of structures that are entirely sustainable is still challenging, industry has shown progress (Schneider et al. 2011) by adopting alternative solutions to conventional concrete such as using recycled aggregates (Naik and Moriconi 2006), binary and ternary mixes with high levels of supplementary cementitious materials (Damtoft et al. 2008, Tikalsky et al 2012), and alternative chemistry binders with a lower carbon footprint than portland cement (Phair 2006). However, mix proportioning guidelines for performance-based specifications have fallen behind these advancements. For selecting the mix proportions, prescriptive-based specifications such as ACI 318 (2011) often refer to ACI 211.1 (1991) which is still the most widely used and most popular concrete mix proportioning guideline despite its inefficiency in reflecting the advancements in concrete technology to the optimization of mix proportioning (Patel and Kinney 2013). Due to being developed prior to the advancements in chemical admixtures such as high-range water-reducing admixtures, and replacement of a portion of ordinary portland cement with supplementary cementitious materials, ACI 211 is conservative in recommending 1) the required water content for the desired slump, and 2) the required water-to-cementitious materials ratio (thereby cementitious materials content) for the desired strength.

This paper addresses the effect of mix proportioning on sustainability by comparing the carbon footprint of cementitious materials proportioned based on ACI 211 guidelines, or proportioned for using other approaches for concrete pavements. The performance criteria for concrete pavements were selected, and the quantity of materials was calculated following the ACI 211 mix proportioning guidelines to achieve the desired workability and strength. Sixty different binary and ternary mixes were proportioned based on performance requirements, which were verified by testing fresh and hardened properties. The comparison between the calculated cementitious materials content recommended by ACI 211 with the required cementitious materials content of performance-based mixes to achieve the same given performance criteria, as well as their associated carbon footprints are presented and discussed.

Methodology

Materials. For performance-based mixes, the following materials were obtained. The chemical composition of the selected cementitious materials is presented in Table 1.

- ASTM C150 Type I ordinary portland cement (OPC)
- ASTM C618 Class C fly ash and Class F fly ash
- ASTM C989 Grade 120 slag cement
- 1-in. nominal maximum size crushed limestone
- No 4 sieve size river sand
- ASTM C260 tall-oil based air-entraining admixture (only used in air-entrained concrete)

Table 1. Chemical composition of the cementitious materials, % by mass

Oxides	OPC	F ash	C ash	Slag
Silicon dioxide (SiO_2)	20.13	52.10	36.70	37.60
Aluminum oxide (Al_2O_3)	4.39	16.00	20.10	9.53
Ferric oxide (Fe_2O_3)	3.09	6.41	6.82	0.44
Calcium oxide (CaO)	62.82	14.10	23.30	40.20
Magnesium oxide (MgO)	2.88	4.75	4.92	11.00
Sulfur trioxide (SO_3)	3.20	0.59	1.88	1.14
Potassium oxide (K_2O)	0.57	2.36	0.48	0.44
Sodium oxide (Na_2O)	0.10	1.72	1.62	0.45
Loss on ignition	2.55	0.09	0.25	0.00

Test Variables. More than one hundred different binary and ternary mixes with a wide range of water-to-cementitious materials ratio (w/cm), cementitious materials content were proportioned, and their corresponding effects on various concrete properties (e.g. surface resistivity, air permeability, shrinkage) were tested. However, for a fair comparison, this paper will only present the performance-based mixes having the same w/cm, air content, and slump range (1-in. to 4-in.) with the mixes proportioned based on the ACI guideline. Therefore, 60 concrete mixtures were selected with the mix characteristics shown in Table 2.

Table 2. Test variables

Variable	Selection
Cementitious system	Reference mixture with 100% ordinary portland cement Binary mixes with Class F fly ash at the replacement level of 15%, 20%, and 30% Binary mixes with Class C fly ash at the replacement level of 15%, 20%, and 30% Binary mixes with slag cement having the replacement level of 20%, and 40% Ternary mixes with 20% of Class C fly ash and 20% of slag cement Ternary mixes with 20% of Class F fly ash and 20% of slag cement
Cementitious materials content	400, 500, 600, and 700 pounds per cubic yard (pcy)
Water-to-cementitious materials ratio (w/cm)	0.35, 0.40, 0.45, and 0.50
Fine-to-total aggregate ratio	0.42
Air content	≤2 % of total air content for non-air-entrained concrete ≤6 % of total air content for air-entrained concrete
Slump range	1-in. to 4-in.

Test Procedures. Four-by-eight in. (4×8-in.) concrete cylinders were prepared in accordance with ASTM C192. Slump, air content, setting time, compressive strength, shrinkage, and durability indicating tests such as rapid chloride penetration, surface resistivity, and air permeability were performed at various ages. However, ACI 211 guideline does not provide any quantitative information regarding the setting time, shrinkage, and durability aspects of the recommended mix components. Therefore, this paper will only compare the expected compressive strength of the mixes proportioned based on ACI 211 and the tested strength values of the performance-based mixes. Other data showing the durability results have been published elsewhere (Yurdakul et al. 2013-a, Yurdakul et al. 2013-b). For a fair evaluation, mixes within the desired slump range of 1 to 4-in. with the same w/cm, and air content were compared. Table 3 presents the summary of the tested properties used for comparison.

Table 3. Tested properties

Concrete properties	Method	No of specimens	Age (days)
Slump	ASTM C143	1	-
Air content	ASTM C231	1	-
Compressive strength	ASTM C39	2	28

Pre-experiments

Mix proportioning based on ACI 211.1 (1991) guidelines. In this research study, mix proportioning for concrete pavements was investigated. Normal-weight and moderate-strength concrete is used for pavements. Therefore, in the first part of this paper, ACI 211.1 (1991) mix proportioning guidelines for normal weight concrete have been followed to determine the cement content required to achieve the desired concrete properties. The following step-by-step procedure will be applied.

Step 1- Choice of slump: According to the Table 6.3.1 in ACI 211, the recommended slump for concrete pavements ranges between 1 and 3 inches.

Step 2- Choice of maximum size of aggregate: The nominal maximum size of coarse aggregate is selected as 1-in. due its local availability and typical usage in concrete pavement applications.

Step 3- Estimation of mixing water and air content: The required mixing water is obtained from Table 6.3.3. Depending on the environmental location of the construction, concrete pavements may be subjected to exposure of freeze-thaw, deicing salts or aggressive chemicals. Therefore, water contents are obtained to account for the following two scenarios:

> First scenario (non-air-entrained concrete): Concrete is not exposed to freeze-thaw, deicing salts, or any aggressive chemicals. Therefore, non-air-entrained concrete will be used. According to the guidelines, the approximate amount of entrapped air is 1.5% for the selected size of aggregate. For the selected aggregate size, the water content is 300 pounds per cubic yard (pcy) to achieve a slump of 1 to 2-in., and 325 pcy to achieve a slump of 3 to 4-in. Since the desired slump for concrete pavements ranges between 1 and 3-in., the required water content for non-air-entrained concrete ranges between 300 and 325 pcy.
>
> Second scenario (air-entrained concrete): Concrete is subjected to exposure of deicing salts or aggressive chemicals; and continuous freezing and thawing. Therefore, air-entrained concrete will be used. According to the guidelines, 6% of air content is recommended for the selected size of aggregate. Given the aggregate size and exposure condition, the water content is 270 pcy to achieve a slump of 1 to 2-in., and 295 pcy to achieve a slump of 3 to 4-

in. Therefore, the required water content for air-entrained concrete ranges between 270 and 295 pcy for the desired slump of concrete pavements.

Step 4- Selection of water-to-cementitious materials ratio (w/cm): Concrete pavements require moderate-strength mixes with 28-day compressive strength ranging between 3000 and 6000 psi (GangaRao et al. 2006). According to Table 6.3.4 (a) in ACI 211, recommended w/cm ranges between 0.40 and 0.59 for air-entrained concrete, and 0.41 to 0.68 for non-air-entrained concrete. Since, the slump requirement of concrete pavements is maximum 3-in., selecting a higher end of the recommended w/cm, such as 0.59 and 0.68, will result in exceeding this limit. Therefore, in this study, both for air-entrained and non-air-entrained concrete, w/cm of 0.40, 0.45, and 0.50 will be selected which are typical for concrete pavements. According to ACI 211 guidelines, w/cm is determined by the specified compressive strength at 28-day and durability concerns depending on the environmental exposure conditions (whichever criteria would lead the minimum w/cm should determine the w/cm). Table 6.3.4 (b) of ACI 211 provides the limiting w/cm values for exposure conditions. According to this information, the maximum permissible w/cm is 0.50 for structures that are continuously or frequently wet and exposed to freezing and thawing. Since the construction type used in this study is concrete pavements, the selected w/cm range of 0.40, 0.45 and 0.50 is within the limits recommended by ACI 211 for severe exposure conditions. The strength-w/cm relationship provided under Table 6.3.4 (a) in ACI 211 is plotted to determine the corresponding strength values of the selected w/cm (Figure 1). The corresponding 28-day compressive strength values of the selected w/cm are interpolated and the calculated values are presented in Table 4.

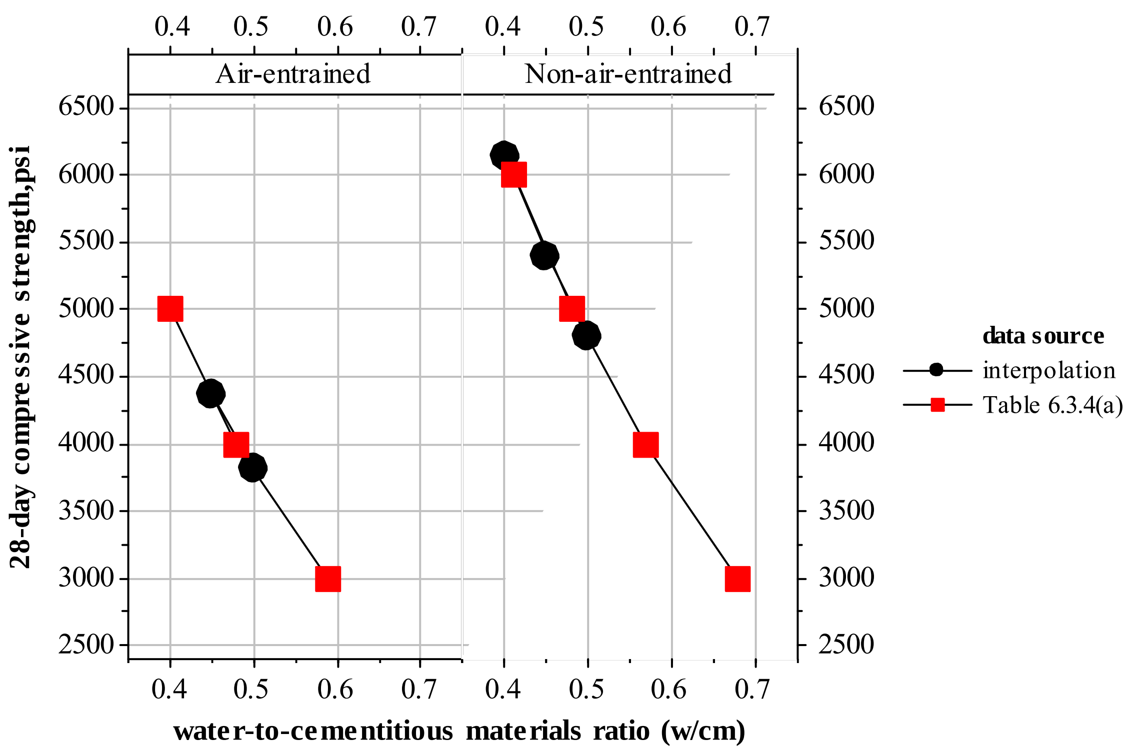

Figure 1. Strength-w/cm relationship provided in Table 6.3.4 (a) in ACI 211, and the interpolated strength of the selected w/cm.

Table 4. Corresponding 28-day compressive strength values of the selected w/cm

w/cm	28-day compressive strength, psi	
	Non-air-entrained	Air-entrained
0.40	6140	5000
0.45	5400	4370
0.50	4800	3820

Step 5- Calculation of cementitious materials content: After determining the water content range required for the desired slump and selecting the w/cm to meet the desired strength requirement, cementitious materials content is calculated and presented in Table 5. The recommended cementitious materials content ranges between 600 to 813 pcy for non-air-entrained concrete, and 540 to 738 pcy for air-entrained concrete.

Table 5. Cementitious materials content recommended by ACI 211 for the desired compressive strength range

w/c	Non-air-entrained concrete			Air-entrained concrete		
	28-day compr. strength, psi	Water content, pcy	Cement content, pcy	28-day compr. strength, psi	Water content, pcy	Cement content, pcy
0.40	6140	300-325	750-813	5000	270-295	675-738
0.45	5400	300-325	667-722	4370	270-295	600-656
0.50	4800	300-325	600-650	3820	270-295	540-590

Results and discussion

Comparison of the cementitious materials content of each proportioning method to achieve a given performance criteria. In this section, tested results of the performance-based mixes were compared with the calculated quantities of the mixes proportioned based on ACI 211 as described in the previous section. For performance-based mixes, no restrictions were applied on the type and content of the cementitious materials since the main goal in proportioning was to ensure meeting the desired performance criteria shown below:

Workability: Slump of 1 to 4-in.
Strength: 28-day compressive strength of 3000 to 6000 psi
Air content: ≤2% for non-air-entrained concrete, ≤6% for air-entrained concrete
Durability: Although durability is a key factor affecting the life span and serviceability of concrete, this study will not present any durability results since ACI 211 does not provide any quantitative information.

Figure 2 shows the comparison between the cementitious materials content recommended by ACI 211 (circle-shaped) and the amount used in the performance-based mixes (square-shaped) to achieve the desired compressive strength at 28-days. The results show that for the selected cementitious system with the chemical compositions shown in Table 1, all the performance-based mixes either required lower cementitious content to achieve the same strength, or resulted in higher strength when the same cementitious materials content was used. The findings are summarized in Tables 6 and 7.

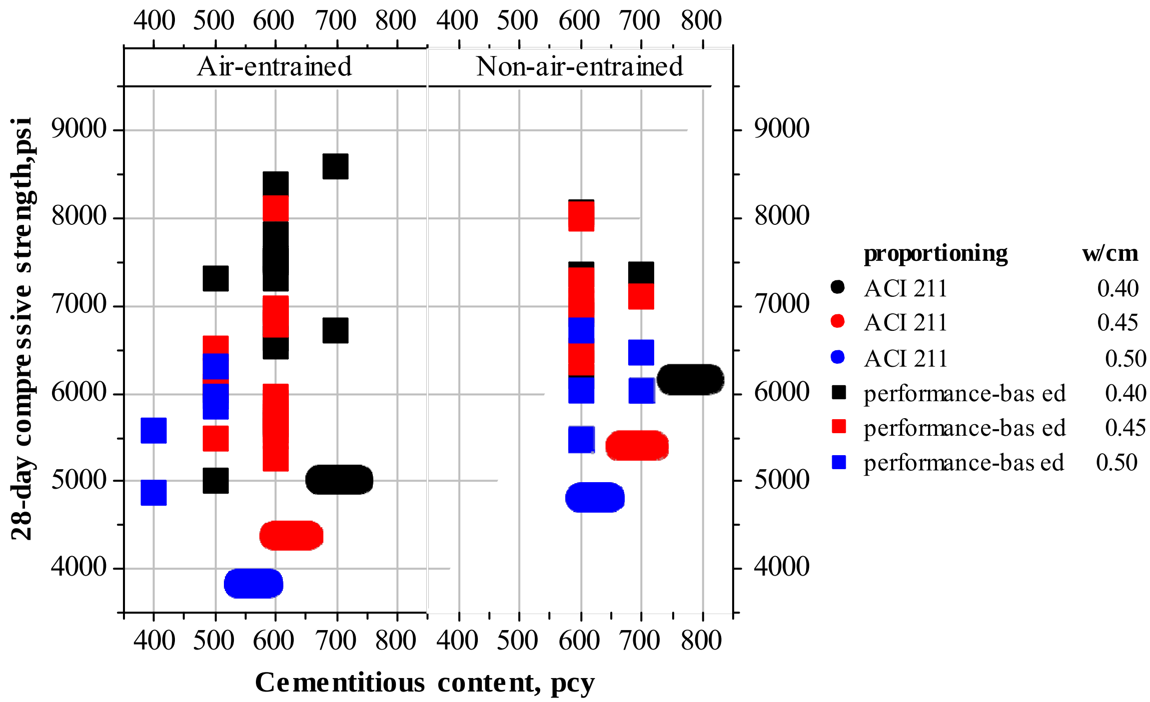

Figure 2. Comparison between the cementitious materials content recommended by ACI 211 and the amount used in experiments for the desired compressive strength at 28-days.

Table 6. The summary of the differences in cementitious materials recommended by ACI 211 compared with performance-based mixes, and their corresponding strength comparison for air-entrained concrete mixtures

w/cm	Cementitious materials content, pcy			28-day compressive strength, psi		
	ACI 211	perfomance based	excessive amount	Expected strength (ACI 211)	Obtained strength (perf. based)	Difference
0.40	675-738	500	175-238	5000	5010-7300	10-2300
0.40	675-738	600	75-138	5000	5650-8380	650-3380
0.40	675-738	700	0-38	5000	6720-8600	1720-3600
0.45	600-656	500	100-156	4370	5480-6520	110-2150
0.45	600-656	600	0-56	4370	5260-8100	890-3730
0.50	540-590	400	140-190	3820	4880-5570	1060-1750
0.50	540-590	500	40-90	3820	5850-6320	2030-2500
Average			*76-129*			*920-2770*
Range			*0-238*			*0-3730*

Table 7. The summary of the differences in cementitious materials recommended by ACI 211 compared with performance-based mixes, and their corresponding strength comparison for non-air-entrained concrete mixtures

w/cm	Cementitious materials content, pcy			28-day compressive strength, psi		
	ACI 211	perfomance based	excessive amount	Expected strength (ACI 211)	Obtained strength (perf. based)	Difference
0.40	750-813	600	150-213	6140	6190-8060	50-1920
0.40	750-813	700	50-113	6140	7360	1220
0.45	667-722	600	67-122	5400	7100	1700
0.45	667-722	700	0-22	5400	6350-8030	950-2630
0.50	600-650	600	0-50	4800	5480-6720	680-1920
0.50	600-650	700	0	4800	6030-6480	1230-1680
Average			*45-87*			*970-1850*
Range			*0-213*			*50-2630*

Tables above show that ACI 211 guideline recommends up to 238 pcy and 213 pcy more cementitious materials content than indicated by the mixtures with the selected cementitious materials, for air-entrained and non-air-entrained concrete, respectively. Furthermore, for mixtures having similar w/cm, cementitious materials content, and air content, performance-based mixes resulted in higher compressive strength test results (up to 3730 psi) than the expected values based on ACI 211.

Supplementary cementitious materials (SCM) reduce the overall carbon dioxide emission of concrete due to being a byproduct and having lower carbon emission than ordinary portland cement (NRMCA 2012). Therefore, in this study, binary and ternary mixes were included to compare their tested compressive strength with the expected strength of mixes having the same w/cm, air content, and slump that are proportioned based on ACI 211.

In the following figures, mixtures were color-coded to differentiate between the mixes incorporating various supplementary cementitious materials (SCM). Figure 3 shows the comparison between the expected compressive strength of the plain concrete mixes that are proportioned based on the ACI 211 guidelines and the tested compressive strength of the performance-based proportioned plain, binary, and ternary mixes having a fixed w/cm of 0.40. For air-entrained concrete with a w/cm of 0.40, ACI 211 recommends using 675 pcy to 738 pcy of ordinary portland cement to ensure achieving 5000 psi of compressive strength at 28-days. However, the results show that 500 pcy of cementitious content at 20% slag cement will achieve the same performance. Furthermore, when plain concrete was used for a head-to-head comparison, despite having approximately 200 pcy less cement, its corresponding strength at 28-days resulted in 1000 psi higher than the value expected by ACI 211. The same behavior is also observed when comparing the air-entrained concrete with 700 pcy of cementitious materials content having a strength range of 6715 psi (with plain concrete) to 8600 psi (containing 20% of slag cement) which was expected to be 5000.

On the other hand, for non-air-entrained concrete with a w/cm of 0.40, ACI 211 recommended use of up to 813 pcy of ordinary portland cement to achieve 6140 psi of compressive strength at

28-days. However, the obtained test results show that a strength of between 6140 and 8060 psi could be achieved with plain, binary, and ternary mixes having a cementitious materials content of 600 pcy. Furthermore, a portland cement content of 813 pcy also brings along potential performance-related problems such as increased heat of hydration, and shrinkage-related cracking. Previous studies (Yurdakul et al. 2013-a) have shown that increasing the cementitious materials content increases strength up to a limit, and then strength becomes independent of the cementitious materials content for a fixed w/cm. Furthermore, it is also reported in the literature (Liu et al. 2012, Mehta and Burrows 2001) that cementitious materials content such as 700-800 pcy are too high to obtain crack-free, durable, and sustainable structures.

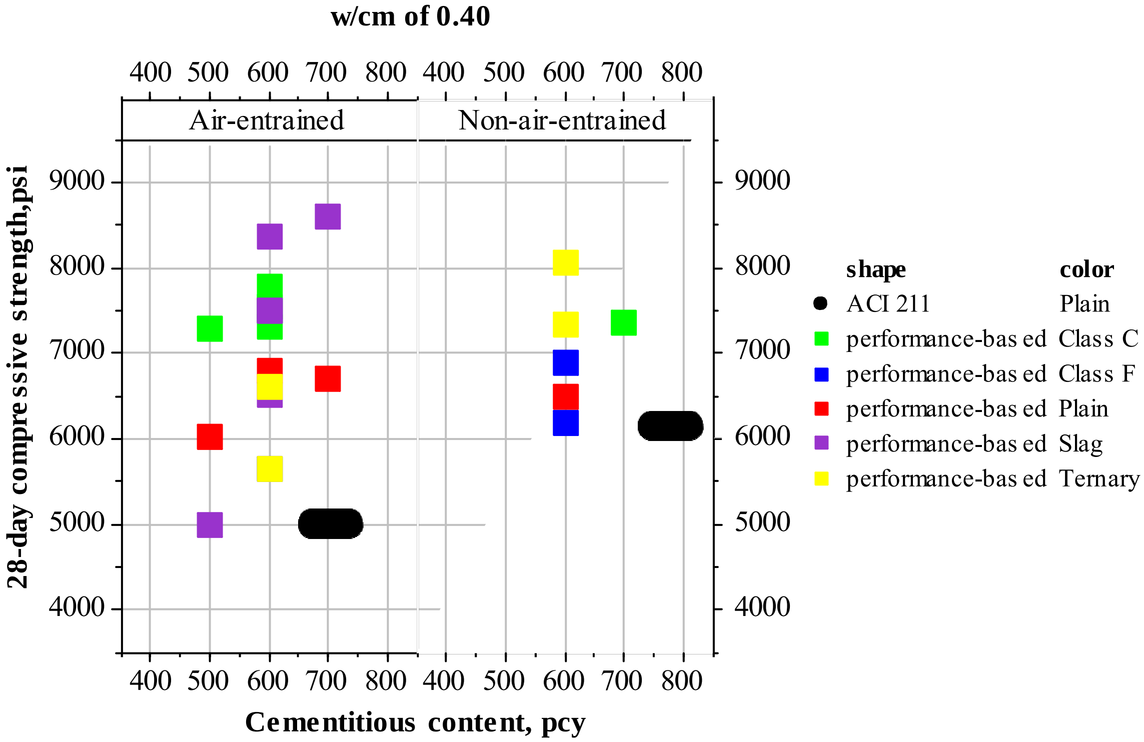

Figure 3. Comparison between the cementitious materials content recommended by ACI 211 and the amount used in performance-based mixes, for a given w/cm of 0.40.

Figure 4 shows the comparison between the expected compressive strength of the mixes proportioned based on the ACI 211 guidelines and the tested compressive strength of the performance-based mixes having a fixed w/cm of 0.45. The performance-based mixes required approximately 100 pcy of less cementitious materials content while providing compressive strength of 2630 psi to 3730 psi more than that of expected by ACI 211, for non-air-entrained concrete and air-entrained concrete, respectively.

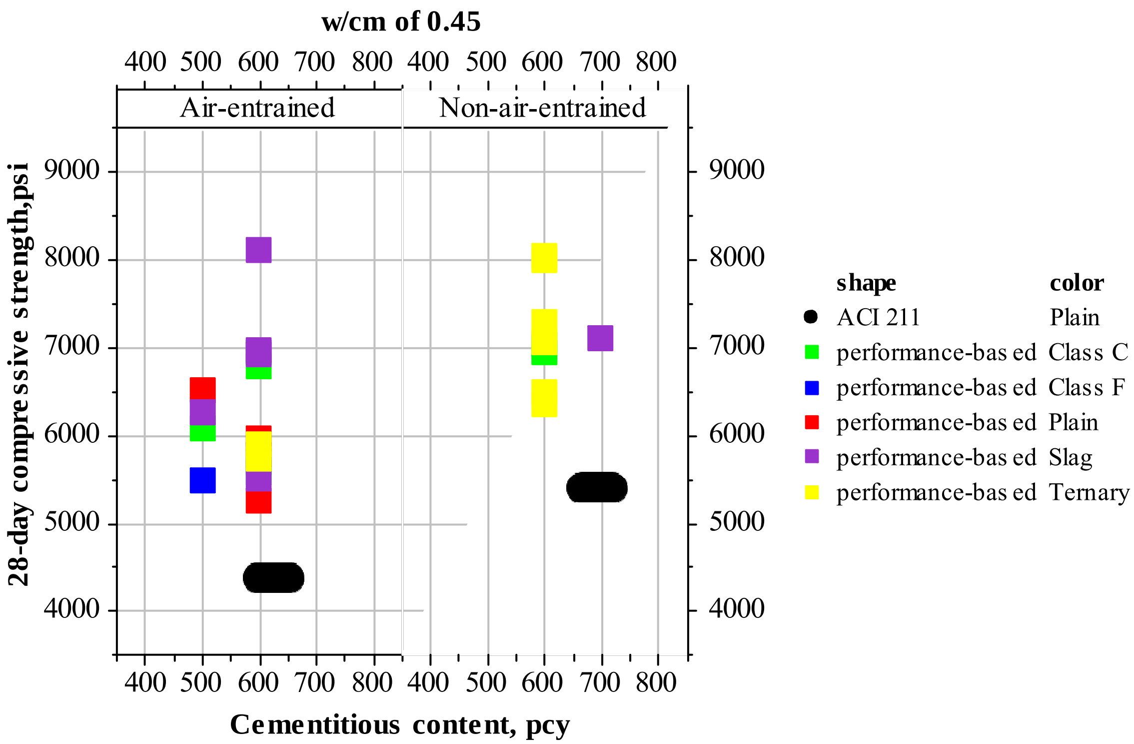

Figure 4. Comparison between the cementitious materials content recommended by ACI 211 and the amount used in performance-based mixes, for a given w/cm of 0.45.

Figure 5 shows the comparison between the expected compressive strength of the mixes proportioned based on the ACI 211 guidelines and the tested compressive strength of the performance-based mixes having a fixed w/cm of 0.50. The obtained results are similar to the mixes with w/cm of 0.40 and 0.45, which indicates the ACI 211 guideline recommended higher cementitious materials content to achieve a certain degree of strength than needed, for the materials used in this work. The degree of benefit in strength provided by SCM depends on the selected type and replacement level of the SCM. However, among all the tested mixes, binary mixes containing slag cement often resulted in the highest strength compared to the other mixes, for a given w/cm and cementitious materials content. Ternary mixes incorporating 20% fly ash and 20% slag cement, and binary mixes with 20% of Class C fly ash also provided higher strength than binary mixes with Class F fly ash and plain concrete. Due to the reduced cement content requirement for a given performance criteria and promoting the usage of SCM, these optimized mixes will be more cost-efficient and sustainable than the plain concrete proportioned based on ACI 211 guidelines.

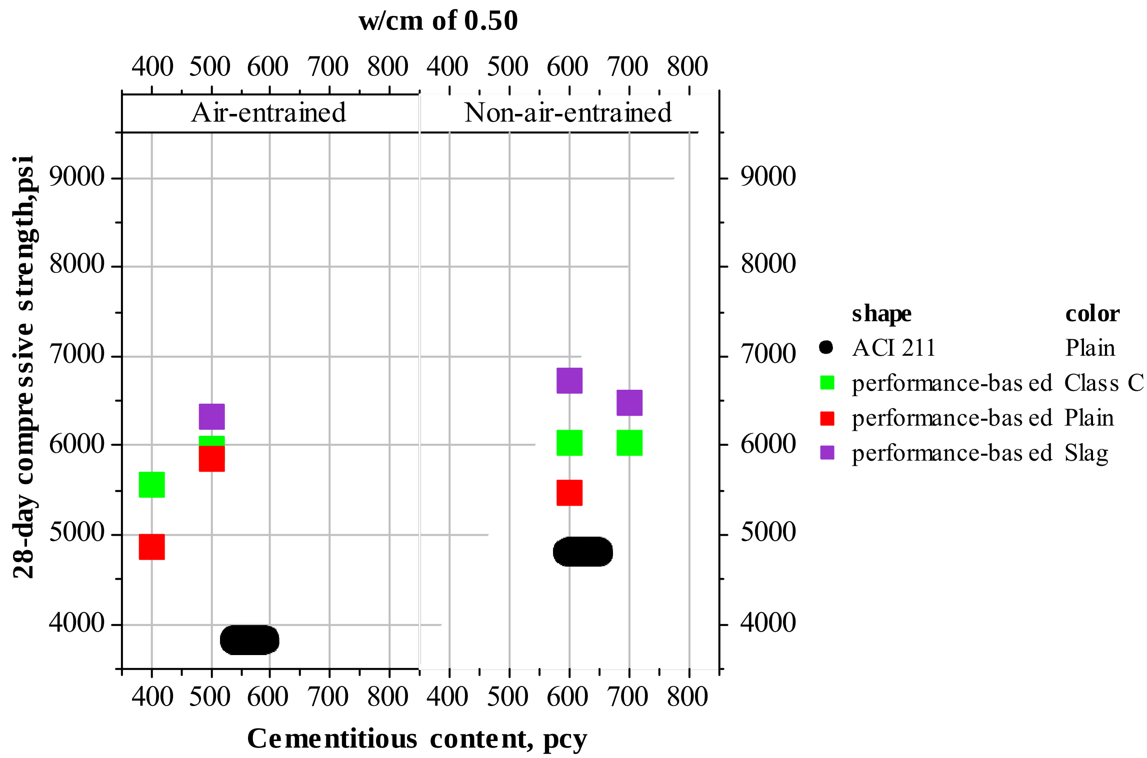

Figure 5. Comparison between the cementitious materials content recommended by ACI 211 and the amount used in performance-based mixes, for a given w/cm of 0.50.

Comparison of the carbon footprint of each proportioning method. In this section, the corresponding carbon footprints of each proportioning method were compared based on the type and amount of cementitious materials used.

According to a survey conducted by the Portland Cement Association (PCA) members, an average of 0.927 ton of CO2 are emitted for every tonne of portland cement produced in the USA (NRMCA 2012, Marceau et al. 2006). Flower and Sanjayan (2007) reported that the emissions factor of fly ash is 0.027 t of CO2/t, and 0.143 t of CO2/t for slag cement. The carbon emission of the performance-based mixes were compared with the carbon emission of the mixes proportioned based on ACI 211 in Figure 6.

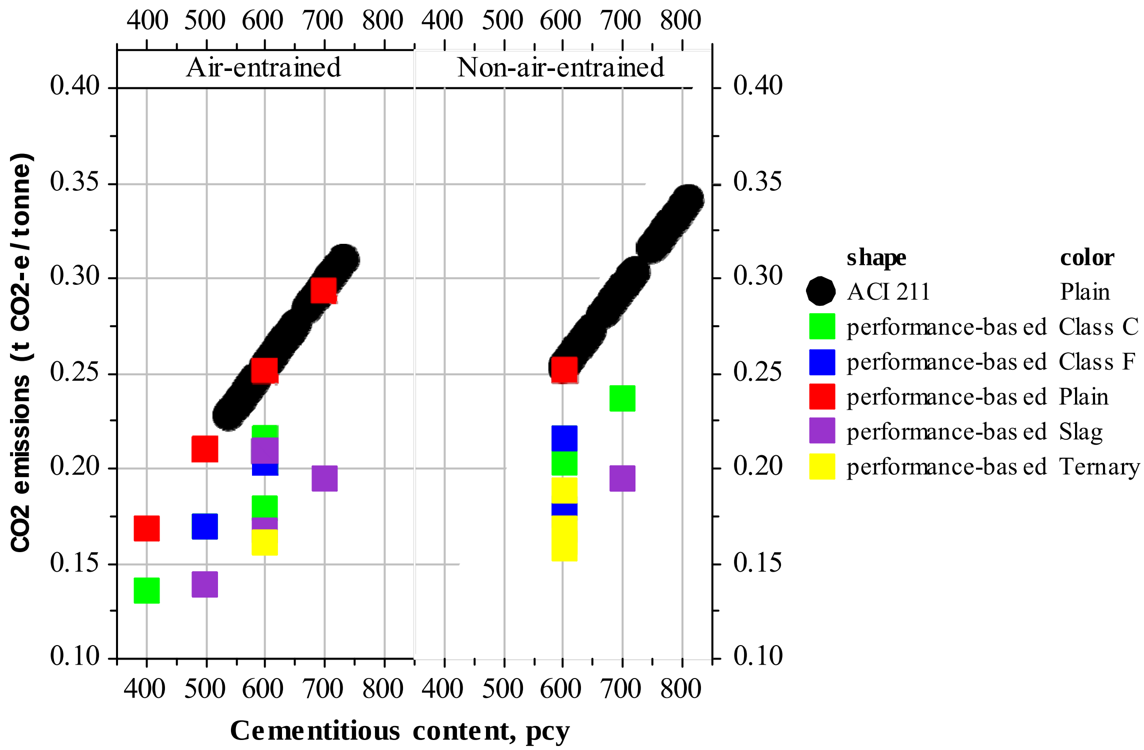

Figure 6. Comparison between the carbon dioxide emissions of the performance-based mixes and the mixes proportioned based on the ACI 211 guidelines.

According to Figure 6, mixes prepared in accordance with the ACI 211 guideline resulted in higher carbon dioxide emissions than the performance-based mixes. Binary and ternary mixes incorporating SCM reduced the carbon dioxide emission of the overall concrete mixes compared to the plain concrete. With the addition of SCM, it may be possible to reduce the required cementitious content up to 238 pcy while achieving the desired performance criteria and reducing the carbon dioxide emissions approximately from 0.35 t to 0.15 t.

Conclusions

Based on the obtained test results, following conclusions can be drawn:

The degree of benefit in strength provided by SCM depends on the selected type and replacement level of the SCM. However, among all the tested mixes, binary mixes containing slag cement and ternary mixes generally resulted in the highest strength and the lowest carbon emissions compared to the other mixes.

Based on the chemical composition of the selected cementitious system, if mixes are proportioned based on performance and optimized with the incorporation of SCM, it may allow us to use less cementitious content than that is recommended by ACI 211 while achieving the desired performance criteria and reducing the carbon dioxide emissions approximately from 0.35 t to 0.15 t.

ACI 211 guideline is found to be conservative in recommending cementitious materials content to achieve a certain degree of strength.

ACI 211 is a reasonable starting point to guide for mix proportioning. However, due to its conservative nature that accounts for unexpected factors that may result in reduced concrete quality, for improved sustainability, one should conduct trial mixes to optimize the mix proportions that can achieve the desired performance efficiently for the available materials.

The results presented in this study are only applicable for the selected cementitious system with the presented chemical composition. Further research is needed to investigate the durability aspect of this approach with the selected w/cm and cementitious content, and the applicability of the findings on concrete with cementitious materials having different chemistry, particle fineness, type, and replacement level than the ones used in this study.

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