Assessing the Effects of Supplementary Cementitious Materials on the Performance of Low-Cement Roller Compacted Concrete Pavement

Farshid Vahedifard[1]; Mahmoud Nili[2]; Christopher L. Meehan[3]

Abstract: Roller compacted concrete pavements (RCCP) are widely used for a variety of industrial and heavy-duty pavement applications that involve low speed traffic. The aim of this investigation is to evaluate the effects of using supplementary cementitious materials - silica fume and pumice - on the workability, compressive strength, and frost resistance of non-air-entrained low-cement content RCCP mixtures. Eight different RCCP mixtures were produced with four types of binder and two binder contents. A series of consistency, compressive strength, and long-term freeze-thaw tests were conducted. Test results indicate that the frost resistance of the low-cement RCCP mixtures improves with higher cementitious materials content. The addition of 10% silica fume increased both the compressive strength and frost resistance of the RCC mixtures; however, it significantly decreased the workability of fresh mixtures. The pumice made the specimens more workable, but had a negative impact on both the compressive strength and frost resistance.

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Keywords: Roller compacted concrete; Freezing and thawing; Compressive strength; Workability; Pumice; Silica fume.

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1 Introduction

Roller compacted concrete (RCC) is a durable and strong building material that has seen increased utilization in recent years. Construction with RCC is a relatively efficient and cost effective process, and consequently it has seen increased use for low-speed concrete pavements in areas such as parking lots, ports, storage areas, military roads, secondary roads, and industrial manufacturing facilities [1,2]. When used as a paving material, RCC is comprised of a relatively stiff mixture of sand and gravel (usually with a maximum aggregate size less than or equal to 19 mm), cementitious materials, water, and in some cases admixtures that are used to improve RCC performance and facilitate the placement process. Typically, RCC constituents are blended in a mixing plant and placed by asphalt paving equipment in layers less than or equal to 25 cm. They are then compacted using steel wheel vibratory rollers [2,3]. The use of RCC as an alternative construction material for industrial and heavy-duty pavements has shown initial cost savings in the range of 10-58%, as compared with the use of conventional paving concrete [4].

Roller compacted concrete pavement (RCCP) is placed and compacted using the same approach as what is commonly utilized for soil layers. Consequently, construction with RCC does not require as much prior preparation or post-placement treatment as what is required for conventional concrete construction; typical concrete processes such as framework and forming, placement of reinforcing steel, or surface finishing are not necessary. Additionally, a number of the inconveniences that are sometimes present when working with prefabricated concrete slabs are not present, such as dealing with joints, surface alignment, and dowels. As a result, RCCP construction requires less equipment and RCC material can be placed in a more time-efficient manner than conventional concrete [2].

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Additionally, with proper mix design, the drier nature of RCCP mixtures allows for strengths that are greater than conventional concrete pavements at the same cementitious materials content [2,5].

Historically, RCC has been used with success on a variety of large earth dam projects. RCCP mixtures are typically different than roller compacted concrete dam (RCCD) mixtures, as they usually have a higher binder content, lower water to cementitious materials ratio (w/cm), smaller maximum aggregate size, higher compressive strength, and higher Vebe time [6].

One of the most important properties of a RCCP mixture is its *workability*, which is a characteristic property that indicates the amount of energy that is required to achieve the maximum density of the aggregates in the mixture [7]. Workability controls the ease of placement and compaction of RCCP layers in the field, the homogeneity of the final compacted pavement, and the long-term RCCP performance, including its mechanical properties and durability [8]. The most common method for evaluating RCCP workability is ASTM C1170, Procedure A, which is the standard test method for determining consistency and density of roller compacted concrete using a vibrating table [9]. This test consists of vibrating a RCC specimen under an applied vertical surcharge of 22.7 kg, and the resulting "Vebe time" (a measure of workability), is the time required to form a ring of mortar around a Plexiglas plate on the top of the specimen. The common range of optimum Vebe times for RCCD mixtures is 10-25 s [6], for tests conducted in accordance with ASTM C1170 [9]. ACI 325.10 R indicates that an appropriate Vebe time for a RCCP is between 30 and 40 s [2]; however, others have reported positive experiences from successful RCCP projects where this range falls between 50 and 75 s [3]. This means that RCCP mixtures are drier, less workable, and need higher compaction energy than do RCCD mixtures. RCC workability is primarily a function of paste volume and fluidity, which should be adjusted for each project based on project specifications and requirements. A workable RCCP should contain enough flowable paste to fill all the voids between aggregates with a reasonable amount of compactive effort. Excessively high workability, which happens because of too much water or paste in the mixture, should be avoided. Excessively workable RCCP mixtures can cause serious problems during placement and compaction, and usually have problems with strength and long-term durability [8].

Another common design parameter of interest in RCC mix design is the *compressive strength* of hardened specimens. Like conventional concrete, the w/cm ratio, the type and amount of cementitious materials, and the aggregate characteristics significantly govern the compressive strength of hardened RCC specimens. The required compressive strength for RCC is usually assigned based on project specifications, where the project application, service load, and durability requirements will govern the selected strength requirements. For RCCD applications, required compressive strengths are typically between 10 and 25 MPa [7]. For RCCP applications, ACI 325.10R recommends a minimum compressive strength of 27.6 MPa, if the RCCP is to be used as a surface course [2]. As RCC is a "dry concrete", its mix design can be optimized to achieve improved compressive strengths by focusing on the dry particles skeleton (i.e. aggregates and cementitious materials) and paste volume [3]. In recent years, these two components of the RCCP mix design process have been optimized using theoretical models such as the optimal volume paste method, the solid suspension model, and the compressible packing model [3,6,7]. Using these models, RCCP specimens have demonstrated the same compressive strengths as conventional concrete mixtures, with 20-28% less binder content [10]. This reduction in required binder content is primarily due to the optimized compactness of the RCCP aggregate skeleton [8].

For many RCCPs, *frost resistance* is another critical design parameter. As pavements are directly exposed to frost everywhere in colder locales, many RCCPs need to address the problems caused by frost action as part of their mix design. In contrast, for RCCD projects, the frost resistance of the RCC is generally not a major concern, because much of the RCC material that is placed is in the inner portion of the dam, and is not directly exposed to frost action. Typically, the parts of a dam that are exposed to frost will be constructed out of conventional air-entrained concrete, which is not susceptible to frost damage [11,12].

As noted in ACI 325.10R, insufficient evidence exists to support the use of RCC for creating "frost resistant" pavements, and more results are needed before final judgment can be made [2]. A number of articles have been published in recent years to investigate the frost resistance of RCCPs, e.g. [3,5,7,11-18]. While field observations for several RCCP projects have reported adequate performance against freeze-thaw cycles in the field, some unacceptable laboratory results have been reported when RCCP samples were tested in accordance with ASTM C 666, Procedure A [5,7,19]. As indicated by ACI's recommendations and these conflicting results, it is clear that problems with the frost resistance of RCC represent a continuing challenge for both researchers and practitioners. The problem of frost damage is a particularly challenging one for RCCPs, because it is difficult to entrain air into RCC mixtures because of the small amount of water that is present in the mix, e.g. [7,20-23].

Portland cement and fly ash are the most commonly used cementitious materials in RCC mix design, although a number of other materials are also used for this purpose [2]. RCCD mixtures usually have a higher volume of fly ash or other type of supplementary cementitious materials than do RCCP mixtures [3]. The effect of different types of supplementary cementitious materials on the performance of RCC have been investigated, including: fly ash, silica fume, bottom ash, volcanic ash, blast furnace slag, and other industrial by-products [3,5,16-18,24-27].

Both self-cementing and non-self-cementing fly ashes (ASTM Class C and F) have been used in RCCP mix design, with satisfying results, e.g. [5,16-18,25]. The maximum amount of fly ash used in RCCP mixtures is usually around 20% of the total binder mass [3]. Generally, using fly ash in a RCC mixture increases the fine materials that are present, yielding a more homogeneous paste and greater consistency [8]. In many cases, the addition of fly ash also yields higher compressive strengths, as the microstructure of the resulting RCCP is improved through additional pozzolanic reactions caused by the presence of the fly ash [2,25].

Silica fume is another commonly used mineral additive in RCCP mixtures, that has been shown to improve RCC strength, density, and frost resistance, e.g. [3,5,8,12]. As it has a drying effect on the fresh mixture, it is commonly used in conjunction with a water-reducing admixture [12]. Silica fume is a common additive that is used for creating high strength RCCP mixtures (e.g. 28-day compressive strengths larger than 65 MPa); the maximum amount of silica fume in the mix is usually limited to 10% of the total binder mass [3].

As noted by Marchand et al. [24], adding silica fume and fly ash to a dry concrete mix (such as a RCCP mix) can result in a more uniform distribution of water during the mixing process. This enhanced water distribution may be attributed to the addition of spherical fines to the dry RCC mixture, which is believed to reduce the internal friction of the paste [24]. Silica fume and fly ash were also found to improve the microstructure of the cement paste in RCC mixtures, through improved spatial distribution of the hydrates and the consumption of portlandite by the pozzolanic reactions, which yield a denser matrix [24].

In practice, RCCP mixtures are commonly designed using a total cementitious materials content of 300 kg/m^3 or higher, e.g. [7,15,21]. Additionally, limited data exists in the literature on the effect of utilizing natural pozzolans (e.g. pumice) as a portion of the cementitious materials in the RCC mixture. This paper presents the results from a series of workability, strength, and non-destructive durability tests that were performed on low-cement RCCP samples at two different binder contents (approximately 235 and 275 kg/m^3 cementitious materials content, respectively). An additional focus of this study was to examine the effect of supplementary cementitious materials on low-cement RCC performance, with a focus on pumice (a natural pozzolan) and silica fume as the additives of interest. To accomplish this goal, eight different RCCP mixtures were prepared and tested to assess the effects of the cementitious additives on the workability, strength, and frost resistance of the resulting RCC.

2 Test Program

In this study, the relative effect of adding supplementary cementitious materials to fresh and hardened low-cement RCCP samples was explored, with a focus on silica fume and pumice as the binder ingredients of interest. A total of eight different RCCP mixtures were prepared using four different binder combinations and two binder contents. Each of these mixtures was then tested to assess the effects of the cementitious materials on the resulting consistency, compressive strength, and long-term freeze-thaw RCC behavior.

3 Material Characteristics

For this test program, the quantity and type of aggregates used to create the RCC specimens were selected to achieve both the required quality and the appropriate combined aggregate curve. Nearly all of the requirements specified in ASTM C33 for the selection of concrete aggregates were considered, with the exception of the fines content recommendations for materials passing the No. 200 sieve. In RCC construction, it is a common practice to modify the aggregate gradation by adding non-plastic materials that are finer than the No. 200 sieve. To account for this common modification, the sand gradation used in this laboratory study was modified by adding a stone powder to adjust the content that is finer than the No. 200 sieve to between 2% and 8%, as recommended in ACI 325.10R [2].

The maximum size of the aggregate used in this study was limited to 19 mm. Aggregates were used in a saturated surface dry condition. Pertinent data for the aggregates used in this study are provided in Table 1. The combined aggregate grading curves are presented in Fig. 1, along with the corresponding boundaries recommended by the ACI [2] and the US Army Corps of Engineers [28].

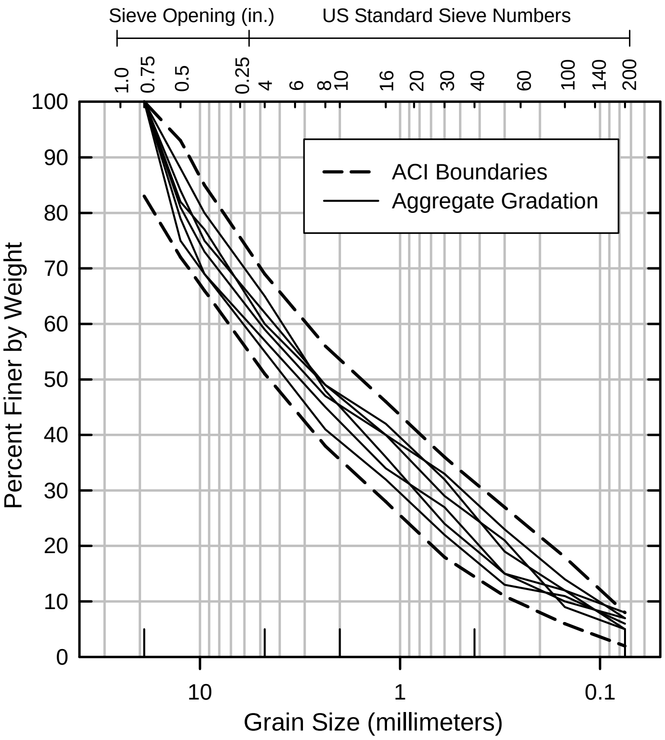

Fig. 1: Combined aggregate grading curves and recommended boundaries.

Type II Cement from the Hekmatan factory in Hamedan, Iran was used in this study. The natural pozzolan was a pulverized Ghorveh pumice (obtained from an area in the north-west of Iran), with particle sizes equal to or finer than ordinary Portland cement. The silica fume was provided by the Semnan Ferrosilice Factory in Semnan, Iran. The properties and characteristics of the pumice and silica fume utilized in this research are shown in Tables 2 and 3, respectively.

4 Mix Proportioning

Appropriate RCCP mix proportioning must meet a number of essential requirements for both the resulting fresh and hardened RCC mixtures. Workability, strength and durability are the basic requirements for the fresh and hardened concrete, respectively [28]. In this research program, RCC mix proportions were selected using soil compaction concepts described in standard practice CRD-C 161-92 [28]. In this practice, the cementitious materials content of a RCC pavement mixture is determined by the w/cm ratio that is necessary to satisfy the strength and durability requirements. The required cementitious materials content is usually expressed as a percentage of the dry mass of aggregate, and typically ranges from 10% to 17%.

In this research, two levels of cementitious materials content (% *cm*) were used: 12% and 15% (about 235 and 275 kg/m^3, respectively). Four combinations of cementitious material type were explored: Type II Cement, Type II Cement + 10% silica fume, Type II Cement + 10% pumice, and Type II Cement + 30% pumice. Silica fume and pumice were treated as partial cement replacement materials.

The optimum moisture content of a RCC mixture is defined as the peak point of the moisture content - wet density curve. ASTM D1557, method D was applied to determine the optimum moisture content. For all eight mixture types used in this study, the optimum moisture content was in the range of 6.2-6.8% of the total dry mass of aggregate. To investigate the effect of cementitious material type and content, the moisture content was fixed at 7% of the total dry mass of aggregate in each mixture. The RCC mix proportions utilized in this study are summarized in Table 4.

5 Casting Procedure

The RCC mixtures were prepared in a counter-current pan mixer. After a 5-min mixing period, a specific mass of RCC was placed in a cylindrical or beam-shaped mold and consolidated using a vibro-compaction apparatus. A modified VeBe Table with a vibration frequency of 60 Hz was utilized for this purpose, as specified in ASTM C1170 [9] and C1176 [29].

There is no standard for casting beam-shaped RCC samples. Traditionally, because of the dry constitution of RCCP mixtures, the use of a vibro-compacting apparatus is employed for supplying the required external energy to ensure adequate compaction [28]. In this investigation, the casting procedure used for the freezing-thawing tests consisted of placing a representative sample of RCC into a beam-shaped steel mold mounted on a standard vibrating table (the modified VeBe test table). Each of the 16 non-air-entrained 80 mm x 100 mm x 400 mm RCC specimens was then consolidated by applying approximately 4.9 kPa to the upper surface of the mold using a steel beam-shaped surcharge load, while the specimen was being vibrated on the VeBe table. For all specimens, the applied vibration time was 2 min. The dimensions of the beam-shaped weight that was utilized in this study were a few mm smaller than the corresponding inside dimensions of the beam-shaped mold. Consequently, during the 2-min consolidation time, all specimens formed a mortar rim between the beam-shaped surcharge and the inside face of the mold. The formation of this mortar rim was caused by a small excess of paste that was expelled from the granular skeleton during vibration, and its appearance indicated that the RCCP had reached its maximum density.

For the compressive strength tests, thirty-two 150 mm diameter x 300 mm tall cylindrical specimens were cast in accordance with ASTM C1176, Procedure A [30], which is the standard for making roller compacted concrete specimens in cylindrical molds using a vibrating table.

6 Laboratory Tests

In order to evaluate the workability of fresh RCC mixtures, the consistency of each mixture was measured in accordance with ASTM C1170 [9]. For each mixture type, three modified VeBe tests were carried out.

To evaluate the compressive strength of the cured RCC mixtures, compressive strength tests were performed on 150 mm diameter x 300 mm tall cylindrical specimens; four of each were cast for each of the eight RCC mixture types. The water cured specimens were capped and tested at the ages of 14 and 28 days after casting (two out of the four specimens were tested at each age).

To assess the durability of the selected mixtures, rapid freezing and thawing tests were conducted on the eight RCC mixture types that were examined in this study, in accordance with the applicable sections of ASTM C666, Procedure A [30]. Two 80 mm x 100 mm x 400 mm beam-shaped specimens were cast from each RCC mixture. Each specimen was then water-cured for 14 days prior to testing. Following the approach outlined in ASTM C666, Procedure A [30], the mass loss and Relative Dynamic Modulus of Elasticity (DME) were obtained for every 50 freezing and thawing cycles on each specimen, for a total of 300 freeze-thaw cycles.

7 Test Results and Discussion

7.1 *Consistency Test Results*

Three modified VeBe tests were performed on each mixture. Based on the results, the average, standard deviation, and maximum and minimum values with a 95% confidence interval are shown in Table 5.

As shown in Table 5, the maximum VeBe time was achieved for the C12S10 mixture (88 s), and the minimum time was measured for the C15P30 mixture (58 s). Table 6 shows the relative effect of increasing the cementitious materials content for each mix, and the effect of changes in the cementitious material type (as compared to the specimens that did not have cementitious material additives) on the average value of the modified VeBe test results. From the results of these tests, the following conclusions can be drawn:

1. The modified VeBe test results exhibited an inverse relationship with cementitious materials content. Using a higher cementitious materials content improved the fresh mixture consistency properties, as indicated by the lower VeBe times that were observed. As shown in Table 6, the VeBe times decreased by at least 10% as the cement content in the mixtures was increased from 12% (C12) to 15% (C15).
2. Addition of 10% pumice to the mixture improved the consistency of C12P10 and C15P10 relative to C12 and C15, and the associated VeBe times decreased from 80 to 76 s. and 72 to 65 s, respectively. For the 30% pumice replacement mixtures, this trend was also observed, with the VeBe time of C12P30 being further reduced to 69 s, and the VeBe time of C15P30 being reduced to 58 s. These results indicate that the addition of pumice to the RCCP mixture can significantly enhance the workability of the resulting RCCP. However, these changes in behavior, which can be beneficial from a constructability standpoint, should not be taken as standalone selection criteria for RCC mix design, as the relative workability of RCC mixtures typically corresponds to changes in the resulting strength and durability behavior of the final RCCP.
3. As shown in Table 5, the RCC mixtures made with silica fume had the highest VeBe time, 88 and 75 s for the C12S10 and C15S10 mixtures, respectively. These results demonstrate that the use of silica fume has an opposite effect on the consistency properties of an RCC mixture than does the use of pumice. The silica fume mixtures tended to be drier in nature, which led to increased VeBe times, and which indicates that this material will likely be more difficult to work with in the field.

7.2 *Compressive Strength Test Results*

The results from the compressive strength tests are summarized in Fig. 2. The test results shown correspond to the average of two strength tests conducted on each mixture. Results are presented for both 14- and 28-day RCC strengths. The error bars shown in Fig. 2 correspond to the maximum and minimum strength values with a 95% confidence interval, based upon the two compressive strength tests that were run for each mixture.

As shown in Fig. 2, the use of silica fume enhanced the strength of the specimens more effectively than the pumice that was utilized in this study. The highest strength results were observed for C15S10, which exhibited compressive strengths of 27.1 and 34.3 MPa at the ages of 14 and 28 days, respectively. The lowest strengths were observed for C12P30, which had compressive strengths of 15.9 and 18.7 MPa at the ages of 14 and 28 days, respectively. Table 7 shows the percent increases in strength for each mix from 14 to 28 days, the relative effect of increasing the cementitious materials content for each mix, and the effect of changes in the cementitious material type (as compared to the specimens that did not have cementitious material additives).

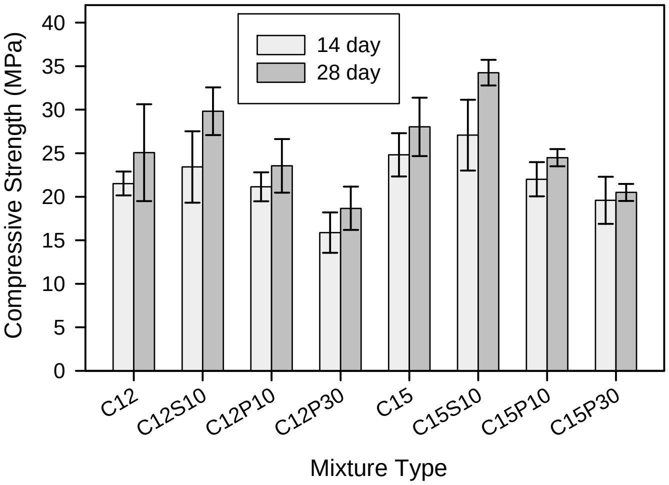

Fig. 2: Compressive strength of different concrete mixtures.

From the results of the strength tests, the following conclusions can be drawn:

1. The most significant percent increases in strength in the 14-28 day period were for the RCC mixes that contained silica fume as an additive. The smallest percent increases in strength were observed for specimens that contained 30% pumice. These data indicate that adding pumice to the mixture enhances the set time characteristics of the RCC, with increasing benefit at increasing pozzolan contents. For mixes that contain silica fume as an additive, the set time characteristics are not as beneficial, as significant strength gain is still occurring from 14 to 28 days.
2. For each type of cementitious material studied, the compressive strength of all mixtures under investigation improved with increasing cementitious materials content. As an example, increasing the cement content from 12% to 15% in the Type II Cement RCC mixtures (C12 vs. C15), showed increases in compressive strength of 15.3% and 11.8% for the 14- and 28-day strengths, respectively. With respect to the 28-day compressive strengths, the most significant increase in strength with increasing cementitious materials content was for the silica-fume-enhanced mixture, and the smallest increase was for the 10% pumice mixture.
3. As compared to the control specimens that did not contain cementitious material additives, those RCC specimens that contained silica fume showed a significant increase in compressive strength. Those RCC mixes that contained the pumice showed significant decreases in strength with respect to the control, with greater decreases at greater pumice content. Compressive strength criteria for RCCP can vary from project to project. However, for RCCP that will be

used as a "surface course", a commonly used criteria is a minimum compressive strength of 27.6 MPa, which is recommended to help ensure adequate long-term concrete performance [2]. None of the mixtures with 12% cementitious materials content (235 kg/m^3), with the exception of the mixture containing silica fume (C12, C12P10, and C12P30), meet this criteria. For mixtures with 15% cementitious materials (275 kg/m^3), the mixtures with pumice (C15P10 and C15P30) could not satisfy this requirement. Consequently, care must be taken in the mix design process when working with pumice as a cement replacement for low-cement RCCP mixtures. Low-cement mixtures containing silica fume exhibited acceptable compressive strengths at both 12% and 15% cementitious materials content.

7.3 *Freezing-Thawing Test Results*

The third objective of the project was to study the effect of supplementary cementitious materials on the freeze-thaw resistance of low-cement RCCP mixtures. As described previously, these tests were carried out in accordance with ASTM C666, Procedure A. In accordance with this test procedure, the cumulative mass loss and Relative Dynamic Modulus of Elasticity (DME) of the RCCP specimens were measured after every 50 freeze-thaw cycles. The test results are presented in Figs. 3 and 4.

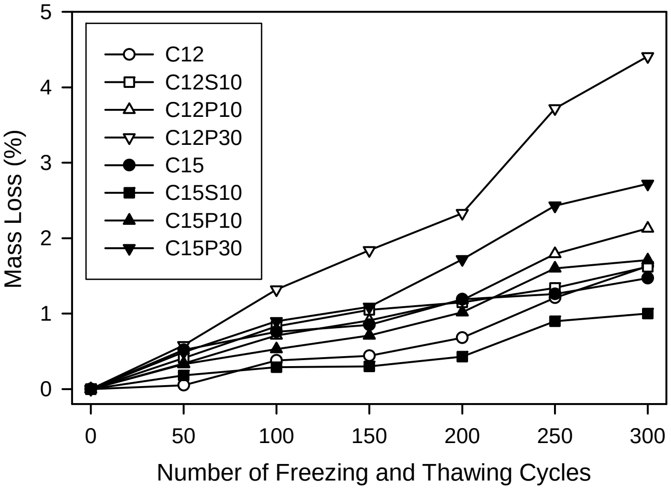

Fig. 3: Cumulative mass loss of RCC samples vs. number of freezing and thawing cycles.

As shown in Fig. 3, after 300 cycles the maximum mass loss that occurred was observed in the C12P30 specimens, and the minimum mass loss was observed in the C15S10 specimens. The corresponding maximum relative DME for C15S10 was equal to 81.5%, and the minimum relative DME for C12P30 was 61.0%. Fig. 5 shows the cumulative mass loss and Relative Dynamic Modulus of Elasticity of the different specimens after 300 rapid freeze-thaw cycles. Mass loss (from maximum to minimum) and DME

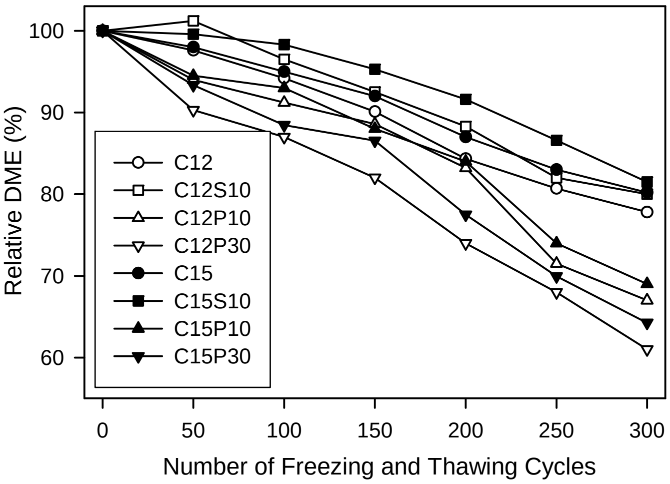

Fig. 4: Relative DME of RCC samples vs. number of freezing and thawing cycles.

(from minimum to maximum) of the specimens are provided in the following order: C12P30, C15P30, C12P10, C15P10, C12, C12S10, C15 and C15S10. The corresponding changes in mass loss and relative DME that result from changing the amount and type of cementitious materials in the mixture are shown in Table 8.

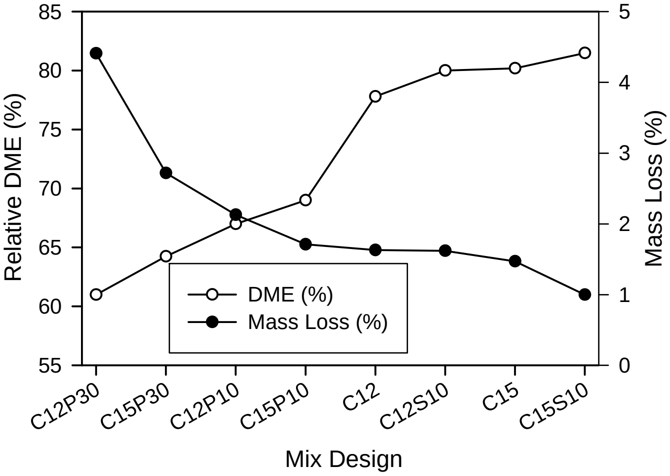

Fig. 5: Comparison of cumulative mass loss and Relative Dynamic Modulus of Elasticity (DME) of RCC samples after 300 rapid freezing and thawing cycles.

The following conclusions can be drawn from the results of the freeze-thaw durability tests shown in Figs. 3 through 5, and from the data shown in Table 8:

1. For each type of cementitious material that was studied, the frost durability of all low-cement mixtures under investigation improved with increasing cementitious materials content, as reflected by the decrease in mass loss and the increase in relative DME. As an example, increasing the cement content from 12% (235 kg/m^3) to 15% (275 kg/m^3) in the Type II Cement

RCC mixtures (C12 vs. C15), showed a 3.1% increase in relative DME and a 9.8% decrease in mass loss. The most significant improvements in frost durability with increasing cementitious materials content were observed for the 30% pumice mix.

2. As compared to the control specimens that did not contain cementitious material additives, those RCC specimens that contained silica fume showed no significant change in relative DME. Very little change in mass loss was observed for the 12% binder content mixtures, while significant change in mass loss (32%) was observed for the 15% binder content mixtures.
3. Those RCC mixtures that contained pumice showed considerable decreases in frost durability with respect to the control, as indicated by their significantly higher mass loss values and their significantly lower DME values. Especially significant decreases in frost durability potential were observed as the pumice content was increased from 10% to 30%. As a result of this observation, it was concluded that the presence of natural pozzolan materials has a significant and negative effect on the frost durability of RCCPs. However, all of the specimens that were tested had relative DME values that were greater than 60%, which means that all of the low-cement mixtures that were tested can reasonably be considered to be “frost resistant” RCCP [30].

8 Conclusion

This study was conducted to evaluate the effects of cementitious material additives on the workability, compressive strength, and frost durability of low-cement RCCP samples. From the results of this research, the following conclusions can be drawn:

1. The results of the VeBe tests indicated that pumice replacement in the mixtures enhanced consistency and workability of the specimens, with respect to control specimens that did not have additives. In contrast, the specimens containing silica fume became drier and less workable.
2. Increases in cementitious materials content from 12% (235 kg/m^3) to 15% (275 kg/m^3) enhanced the workability, compressive strength, and frost durability of RCCP, for all of the mixes that were tested.
3. The use of pumice as a cement replacement produced RCCP specimens that have less frost durability and compressive strength at 28 days than cases where pumice was not used. The resulting workability of the RCC mixes was significantly improved and the frost durability criterion was satisfied with the low-cement, pumice-enhanced RCCP mixtures. However, using the pumice, it was difficult to meet commonly-specified RCC strength requirements. Consequently, pumice appears to be a useful additive for RCCP mixtures for enhancing workability and frost durability. For achieving higher compressive strengths, it is recommended that future mixes be made at higher cementitious materials contents than those used in this study.
4. Silica fume was an effective mineral additive, as it enhanced both the compressive strength and frost durability of the RCCP mixes. However, the workability of silica-fume-enhanced mixtures is less than that of normal RCC mixes. As workability is commonly a significant issue for RCCP placement, this is a concern, and pumice may prove to be a more useful cementitious additive for many field applications where high RCC strengths are not required. For cases where higher strengths or durability are required, it is recommended to use chemical admixtures (e.g. a superplasticizer) to improve the workability properties of silica-fume-enhanced RCCPs.
5. Although the type of natural pozzolan used in the research (pumice) had a negative effect on the 28-day compressive strength, it did show an accelerated rate of compressive strength gain from 14 to 28 days. If a solution can be found to minimize the initial strength reduction effect, it may become possible to use readily available pumice as a partial replacement of aggregate instead of cement replacement when optimizing RCC mixture proportions.
6. All of the low-cement RCCP specimens tested in this study were able to withstand 300 cycles of freezing and thawing in water without any significant deterioration.

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Table 1: Aggregate Properties

Physical properties	Sand	Gravel
Specific gravity (SSD)	2.55	2.67
Water absorption (%)	3.09	2.69
Fineness modulus	2.2	

Table 2: Pumice Properties Compared with ASTM C618 Requirements

Property	Test result	Standard requirement
Chemical properties		
$SiO_2 + Al_2O_3 + Fe_2O_3$ (min.)	77.56%	70.0%
Sulfite (max.)	0.34%	0.4%
Loss on ignition (LOI)	0.48%	10%
CaO	12.88%	-
Mn_2O_3	5.4%	-
Chloride	0.014%	-
Physical properties		
Activity index in 7 days (min.)	75.5%	75%
Activity index in 28 days (min.)	96%	75%
Specific gravity	2.91	

Table 3: Characteristics of Silica Fume

Oxides	
SiO_2	85.0%
Al_2O_3	0.5%
Fe_2O_3	0.4%
MgO	0.1%
Na_2O	0.15%
K_2O	0.15%
Loss on ignition (LOI)	1.5%
Physical properties	
Specific gravity	2.21

Table 4: RCC Mix Designs Utilized in the Study

Mixture	Cementitious materials (kg/m^3)			Water (kg/m^3)	w/cm	Sand (kg/m^3)	Gravel (kg/m^3)
	Portland cement	Pumice	Silica fume				
12% cm (Cement Type II)							
C12	238	-	-	98	0.41	1127	918
12% cm (0.9 Type II + 0.1 pumice)							
C12P10	215	22	-	98	0.41	1127	918
12% cm (0.7 Type II + 0.3 pumice)							
C12P30	167	67	-	98	0.42	1127	918
12% cm (0.9 Type II + 0.1 silica fume)							
C12S10	215	-	17	98	0.42	1127	918
15% cm (Cement Type II)							
C15	281	-	-	128	0.46	1064	867
15% cm (0.9 Type II + 0.1 pumice)							
C15P10	253	26	-	128	0.46	1063	867
15% cm (0.7 Type II + 0.3 pumice)							
C15P30	197	79	-	128	0.46	1064	867
15% cm (0.9 Type II + 0.1 silica fume)							
C15S10	253	-	20	128	0.47	1064	867

Table 5: Modified VeBe Test Results

Mixture	Modified VeBe (s)			
	Average	Standard deviation	Max. with 95% CI	Min. with 95% CI
C12	80	2.6	83	77
C12S10	88	2.1	90	85
C12P10	76	1.5	78	75
C12P30	69	3.1	73	66
C15	72	2.0	74	70
C15S10	75	2.5	78	72
C15P10	65	3.2	69	62
C15P30	58	1.7	60	56

Table 6: Effect of Cementitious Materials Content and Type on Modified VeBe Test Results

Mixture	Cement content effect[a] (%)	Cement type effect[b] (%)
C12		0.0
C12S10		9.6
C12P10		-4.6
C12P30		-13.3
C15	-10.0	0.0
C15S10	-14.1	4.4
C15P10	-14.4	-10.2
C15P30	-16.3	-24.1

[a] The effect of cementitious material content at the same cementitious material type (e.g. VeBe$_{C15P10}$ = (VeBe$_{C15P10}$ - VeBe$_{C12P10}$)/VeBe$_{C12P10}$).

[b] The effect of cementitious material type at the same cementitious material content (e.g. VeBe$_{C15P30}$ = (VeBe$_{C15P30}$ - VeBe$_{C15}$)/VeBe$_{C15}$).

Table 7: Effect of Age, Cementitious Materials Content, and Type on Compressive Strength Test Results

Mixture	Age effect[a]	Cement content effect[b] (%)		Cement type effect[c] (%)	
	% age	14 days	28 days	14 days	28 days
C12	16.4			0.0	0.0
C12S10	27.3			8.8	19.0
C12P10	11.3			-1.7	-6.0
C12P30	17.6			-26.2	-25.5
C15	12.9	15.3	11.8	0.0	0.0
C15S10	26.5	15.6	14.9	9.1	22.2
C15P10	11.4	4.0	4.1	-11.3	-12.6
C15P30	4.6	23.4	9.8	-21.0	-26.8

[a] Rate of strength gain from 14 to 28 days at the same cementitious material content and type (e.g. C12 = (C12$_{28days}$ - C12$_{14days}$)/C12$_{14days}$).

[b] The effect of cementitious material content at the same cementitious material type and at the same age (e.g. C15S10$_{14days}$ = (C15S10$_{14days}$ - C12S10$_{14days}$)/C12S10$_{14days}$).

[c] The effect of cementitious material type at the same cementitious material content and at the same age (e.g. C12P10$_{28days}$ = (C12P10$_{28days}$ - C12$_{28days}$)/C12$_{28days}$).

Table 8: Effects of Cementitious Materials on Mass Loss and Relative DME after 300 Freezing and Thawing Cycles

Mixture	Cement content effect[a] (%)		Cement type effect[b] (%)	
	Mass loss (%)	Rel. DME (%)	Mass loss (%)	Rel. DME (%)
C12			0.0	0.0
C12S10			-0.6	2.8
C12P10			30.7	-13.9
C12P30			170.6	-21.6
C15	-9.8	3.1	0.0	0.0
C15S10	-38.3	1.3	-32.0	1.0
C15P10	-19.7	3.0	16.3	-14.0
C15P30	-38.3	5.3	85.0	-19.9

[a] The effect of cementitious material content at the same cementitious material type after 300 cycles (e.g. $\mathrm{DME}_{C15S10} = (\mathrm{DME}_{C15S10} - \mathrm{DME}_{C12S10})/\mathrm{DME}_{C12S10}$).

[b] The effect of cementitious material type at the same cementitious material content after 300 cycles at the same age (e.g. $\mathrm{DME}_{C12P30} = (\mathrm{DME}_{C12P30} - \mathrm{DME}_{C12})/\mathrm{DME}_{C12}$).