

# Mix Design Development for Pervious Concrete in Cold Weather Climates

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## ABSTRACT

Portland cement pervious concrete (PCPC) is increasingly being used in the United States in sidewalks and parking lots due to its benefits in reducing the amount of runoff water and improving water quality. In the United States, PCPC typically has high porosity and low strength, which has resulted in limited use of pervious concrete in hard wet freeze environments (i.e., the Midwest and Northeast). The purpose of this research is to develop a PCPC mix that not only has sufficient porosity for stormwater infiltration, but also desirable strength and freeze-thaw durability. In this research, concrete mixes were designed with various sizes and types of aggregates, water-to-binder ratios, binder contents, and amounts of admixtures. Porosity, permeability, strength, and freeze-thaw durability of these mixes were evaluated. Preliminary research results indicated that the use of single-sized aggregate could provide concrete with high porosity but not adequate strength. Above a certain level, increasing cement content resulted in a reduced concrete porosity with insignificant influence on concrete strength. Using sand and latex significantly improved the workability of PCPC and resulted in higher strength, appropriate permeability, and freeze-thaw resistance at 180 cycles to date.

**Key words: freeze-thaw—permeability—pervious concrete—strength**

# INTRODUCTION

## Background

Recent amendments of the Clean Water Act require reductions in the quantity of stormwater runoff and also some amount of initial water quality treatment. The United States Environment Protection Agency (EPA) regulates and monitors compliance by granting National Pollutant Discharge Elimination System (NPDES) permits. The new stormwater policy was implemented in two phases: Phase I NPDES required monitoring and treatment of stormwater by municipalities of 100,000 or greater, industries, and construction sites of five acres or more; and Phase II NPDES increased accountability to municipalities greater than 10,000 people and construction sites greater than one acre (EPA 1996). Individual state departments of natural resources (DNRs) have been charged with enforcing the stricter standards.

One of the methods expected to reduce the volume of direct water runoff from pavement and enhance the quality of storm water is pervious concrete (Water Environment Research Foundation 2005). In the United States, the application of pervious concrete is limited to sidewalks, parking lots, and low traffic density areas. The void ratio and 28-day compressive strength of pervious concrete range from 14% to 31% and 980 psi and 2,830 psi, respectively, with most mixes on the lower side of the compressive strength range (Florida Concrete and Products Association, Inc. 2000; National Ready Mix Association 2004). The National Ready Mix Association (2004) reported the mix design of ten projects where pervious concrete was used in the United States. The mix design used in these projects is summarized in Table 1 (National Ready Mix Association 2004). This table shows that these mixes contain no fine aggregate (i.e., sand) with a water-cement ratio ranging from 0.27 to 0.43. Only one of the reported mixes was installed in a hard wet freeze environment (i.e., the Midwest and Northeast United States) with an average temperature below freezing for 90 days. Although pervious concrete used in the United States has a high void ratio, the 28-day compressive strength is less than that required for structural concrete (i.e., 3,000 psi) (Kosmatka et al. 2002). Low strength values and lack of freeze-thaw resistance has limited the use of pervious concrete in the wet freezing regions (i.e., midwestern and northeastern United States).

This paper summarizes the results of the research performed at the Portland Cement Concrete Research Laboratory at Iowa State University to develop a freeze-thaw resistant pervious concrete that has the required compressive strength and adequate permeability.

**Table 1. Typical mix design of existing PCPC**

<b>Material</b>	<b>Amount/yd<sup>3</sup></b>
Cement	300–600 lbs
Coarse aggregate	2,400–2,700 lb.
Fine aggregate	0
Water/cement	0.27–0.43

## Research Scope

To improve strength and maintain the appropriate void ratio for the PCPC developed in the United States, fine aggregate, supplementary cementitious materials, and admixtures were added to the existing PCPC mixes used in the United States. Mixes that achieved the highest seven-day compressive strength and

appropriate void ratio were further tested for long-term compressive strength, permeability, tensile strength, and freeze-thaw durability.

## MATERIALS

Mixes were prepared using LaFarge Type I/II cement with two types of single-size coarse aggregate: crushed limestone and river gravel. Three single sizes of river gravel (1/2-in., 3/8-in., and No. 4) and one size of crushed limestone (3/8-in.) were used. The single size of aggregate was defined as the size of the sieve on which 100% of aggregate was retained, but onto which all passed through the sieve above. The properties of these aggregates are summarized in Table 2. The dry rodded unit weight and void ratio of aggregates were measured using ASTM C29. The specific gravity and absorption were 2.62 and 1.1% for river gravel and 2.45 and 3.2% for crushed limestone, respectively (ASTM C127 2003). To improve the strength of single-size coarse aggregate mixes, concrete river sand was added. The sand had a fineness modulus of 2.9, specific gravity of 2.62, and absorption of 1.1% (ASTM C136 2003; ASTM C128 2003).

A styrene butadiene rubber (SBR) latex was used to improve the cement-aggregate bond and the freeze-thaw durability. The SBR latex is approved by the Federal Highway Administration for latex-modified concrete used in bridge deck overlays (Dow 2005).

An air entraining agent (AEA) and high-range water reducer (HRWR) were only used in the mixes that did not contain latex. The specific gravity and pH were 1.01 and 10 for air entraining (Everair plus) and 1.07 and 7.8 for the high-range water reducing admixtures (Glenium 3400 NV).

**Table 2. Aggregate characteristics**

Aggregate type	Crushed limestone		River gravel		River sand	
	Aggregate gradation	3/8 in.	No. 4	3/8"		1/2"
Dry rodded unit weight (lbs/ft <sup>3</sup> )		86.5	99.4	100.5	102.5	
Voids (%)		43.5	37.3	38.5	39.2	
Specific gravity		2.45	2.62	2.62	2.62	2.62
Absorption		3.20%	1.10%	1.10%	1.10%	1.10%

## MIX PROPORTIONS

The mix design process was divided into two phases. Phase I was conducted to investigate how aggregate size and cement content influence the void ratio and strength of PCPC. These mix proportions are similar to those summarized in Table 1. After the desirable void ratio and strength were achieved, Phase II was conducted to study the effects of sand addition and silica fume and latex (as a replacement of binder) on the PCPC properties. All mix proportions studied are presented in Tables 3 and 4.

**Table 3. Phase I mixture proportions**

Mix	Aggregate type	Size	Unit weight (lbs/cy)			
			PC	Aggregate	Water	Water/binder
1	River gravel	3/8"	600	2700	162	0.27
2	River gravel	1/2"	550	2700	149	0.27
15	River gravel	#4	578	2700	156	0.27
3	Limestone	3/8"	550	2700	149	0.27

**Table 4. Phase II mixture proportions**

Mix	Aggregate type	Size	PC	Unit weight (lbs/cy)					Water	Water/binder
				Silica fume	Latex	G	S			
12	River gravel	#4	571	-	-	2500	168	154	0.27	
10	River gravel	#4	525	-	52.5	2700	-	116	0.27	
8	River gravel	#4	520	-	52	2500	168	114	0.22	
13	River gravel	#4	542.5	-	28.5	2500	168	130	0.24	
14	River gravel	#4	485.4	-	85.6	2500	168	107	0.22	
19	River gravel	3/8"	571	-	-	2500	168	154	0.27	
5	River gravel	3/8"	522.5	27.5	-	2700	-	149	0.27	
11	River gravel	3/8"	520	52	-	2500	168	114	0.27	
4	Limestone	3/8"	522.5	27.5	-	2700	-	149	0.27	
16	Limestone	3/8"	571	-	57.1	2500	168	126	0.22	
17	Limestone	3/8"	600	-	60	2500	200	132	0.22	

## SPECIMEN PREPARATION

Two batch sizes (0.5 cf and 3 cf) were used during the mix design. Initially, mixes were prepared using a small trial batch (0.5 cf) to perform void ratio and seven-day strength tests. When the results appeared satisfactory, a larger batch (3 cf) was prepared and further investigation was conducted. To improve the bond between aggregate and cement paste, aggregate was first mixed with dry cement for one minute, and then half of the water containing either latex or AEA was added and mixed for one minute. Next, the remaining cement and water (with or without HRWR) was added. Finally, the concrete was mixed for three minutes, allowed to rest for three minutes, and then mixed for an additional two minutes before casting. Specimens were placed by rodding 25 times in three layers along with applying a vibration for five seconds after rodding each layer. The samples were demolded after 24 hours, placed in a fog room at 98% relative humidity, and cured according to ASTM C192. Before compression testing, the cylinders were capped using a sulfur capping compound following ASTM C617.

## TESTING PROCEDURE

Workability of the fresh concrete was determined by a standard slump cone test (ASTM C143). Sulfur-capped samples were tested in compression according to ASTM C39. Cylinders of four x eight inches were used for both compression and tensile strength tests. Splitting tensile tests were performed based on ASTM C496.

The void ratio of pervious concrete was determined using a three- x six-inch cylinder sample by taking the difference in weight between a sample oven dried and a sample under water (Park 2004).

$$V_r = \left[ 1 - \left( \frac{W_2 - W_1}{\rho_w \text{Vol}} \right) \right] 100(\%) \quad (1)$$

Where  $V_r$ =total void ratio, %;  $W_1$ =weight under water, lbs;  $W_2$ =oven dry weight, lbs; Vol=volume of sample, in.<sup>3</sup>;  $\rho_w$ =density of water, lbs/in.<sup>3</sup>.

Permeability was determined using the falling head method through the permeameter illustrated in Figure 1. Samples used in the permeability test were three inches in diameter and three inches in length. A flexible sealing gum was used around the top perimeter of the sample to prevent water leakage along the

sides of the sample. The samples were then confined in a membrane and sealed in a rubber sleeve, which was surrounded by adjustable hose clamps. The test was performed using several water heights that represented values that a pavement may experience. The initial height of water ( $h_1$ ) ranged between two and six inches. The coefficient of permeability ( $k$ ) was determined by the following equation:

$$k = \frac{aL}{At} \text{LN} \left( \frac{h_1}{h_2} \right) \quad (2)$$

Where  $k$ =coefficient of permeability, in./s;  $a$ =cross sectional area of the standpipe, in.<sup>2</sup>;  $L$ =length of sample, in.;  $A$ =cross sectional area of specimen, in.<sup>2</sup>;  $t$ =time in seconds from  $h_1$  to  $h_2$ ;  $h_1$ =initial water level, in.;  $h_2$ =final water level, in. (Das 1998).



**Figure 1. Measurement of permeability for PCPC**

Samples were subjected to freeze-thaw testing according to ASTM C666A, in which the samples are frozen and thawed in the wet condition (see Figure 2). The test was complete when a sample reached 300 cycles or 15% mass loss. Mass loss was tested every 20 to 30 cycles, depending on the stability of the sample. To date, samples have been subjected to 117 and 180 cycles.



**Figure 2. PCPC freeze-thaw test samples**

## RESULTS

The results of Phase I (Table 5) indicate that the void ratio of baseline mixes (mixes 1, 2, 3, and 15) were all above 25%, and the seven-day compressive strength ranged from 1,145 psi to 2,100 psi. Mix 3 (3/8-in. crushed limestone) provided the highest void ratio but lowest compressive strength. Mix 15 (No. 4 river gravel) provided the highest strength and the lowest void ratio.

**Table 5. Phase I results**

Mix	Unit weight (lbs/ft <sup>3</sup> )	Void ratio (%)	Seven-day compressive strength (psi)
1	116.9	28.8	1771
2	112.9	38.8	1145
15	117.5	25.3	2100
3	104.1	33.6	1396

Considering both the void ratio and strength, 3/8-in. and No. 4 gravel was selected for study in Phase II. The results of Phase II are summarized in Table 6. Full-scale batches of mixes 3 and 15 were prepared and tested. The 28-day compressive strength was 2,506 psi and 1,722 psi for mixes 15 and 3, and the permeability was 0.57 in./sec. and 0.098 in./sec., respectively. Adding silica fume to mixes 1 and 3 (i.e., mixes 5 and 4) did not show strength improvement.

**Table 6. Phase II results**

Mix	Unit weight (lbs/ft <sup>3</sup> )	Void ratio (%)	Seven-day compressive strength (psi)	k (in./s)
15	117.5	25.3	2,100	0.098
3	104.1	33.6	1,396	0.57
5	111.6	33	1,347	-
4	98.6	41.8	784	-
19	130.9	20.5	3,262	0.193
11	127.3	20.2	2,641	0.094
12	126.3	19	3,299	0.043
10	135.2	12.9	3,142	-
8	126.8	19	2,969	0.071
13	120.3	26	1,307	-
14	132.2	14.1	2,735	0.016
16	117.4	25.7	2,483	0.185
17	124.6	17.9	2,910	0

The effect of using sand and latex in the mix was also investigated. Including 7% fine sand to baseline mixes 1 and 15 (see mixes 19 and 12) improved the strength by 57% and 84% and reduced the void ratio by 8.3% and 6.3%, respectively. Comparing the results for mixes 19 and 11 (i.e., 3/8-in. river gravel with sand and with sand and latex) showed that the strength and permeability decreased when latex was included in the mix, although both mixes had the same void ratio. As a result, the permeability was reduced from 0.098 in./sec to 0.043 in./sec. when comparing mixes 15 and 12. Adding 10% latex to baseline mix 15 (see mix 10) improved the strength by 50% but reduced the void ratio by 50%. When using both latex and sand (see mix 8), the increase in seven-day compressive strength was less than that

achieved using only sand or latex, and the permeability reduced from 0.098 in./sec to 0.071 in./sec when comparing mixes 15 and 8. Adding sand to mix 15 (see mix 12) improved the tensile strength by 49%. Furthermore, using sand together with latex, the tensile strength improved by 58% (see mix 8).

The effect of the amount of latex added was further investigated using 5% and 15% in mixes similar to mix 8 (see mixes 13 and 14). The results show a decrease of strength in mixes 13 and 14 when compared to mix 8. This result indicates that using 10% latex is the optimum amount for improving strength, workability, and water reduction.

For crushed limestone aggregate mixes, using latex and sand improved the strength by 78% when comparing mix 16 with mix 3. When the cement content was increased to 600 lbs (i.e., mix 17), the strength increased by 108%. However, when comparing mixes 3, 16, and 17, the results indicate that the void ratio reduced from 33.6% to 25.7% and 17.9%, which reduced the permeability from 0.57 in./sec to 0.185 in./sec and 0 in./sec, respectively. Further observations and the trends of strength, permeability, and freeze-thaw for tested mixes are described below.

### Void Ratio and Compressive Strength

As expected, the compressive strength of PCPC tended to decrease as the void ratio increased. For both river gravel and crushed limestone, the reduction of strength as a function of void ratio is linear (see Figures 3 and 4). When comparing the reduction in strength as the void ratio increases for 3/8-in. aggregate size (see equations on Figures 3 and 4), it is observed that although river gravel has higher initial compressive strength (at zero void ratio, 5,558 vs. 4,725 psi), the compressive strength diminished in a faster trend (128.9 vs. 96.6). For river gravel, where three sizes of gravel were tested, it was observed that as the aggregate size increases, the samples fail at the contact between the cement paste and the aggregate; however, the samples fail through aggregate for smaller size aggregate. This is expected, since the cement-aggregate contact area in mixes with large-size aggregate is smaller.

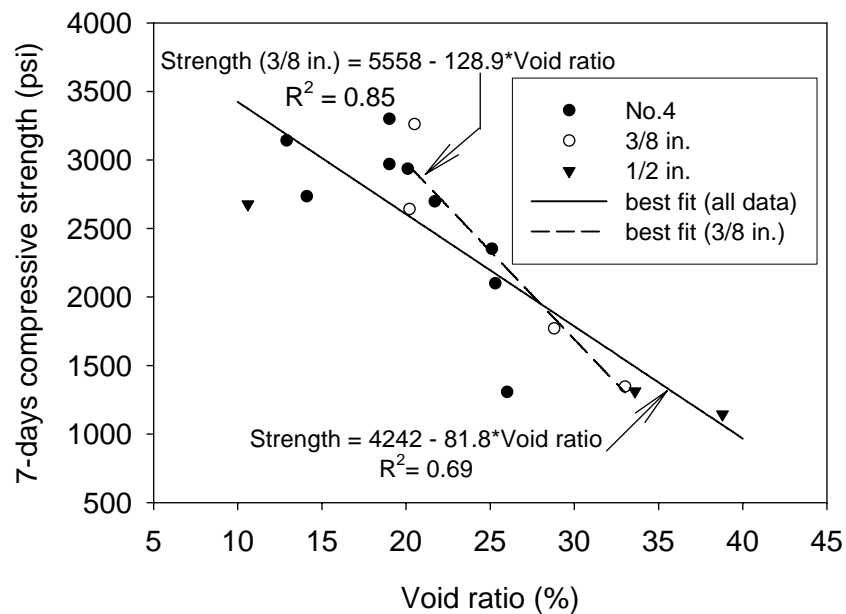
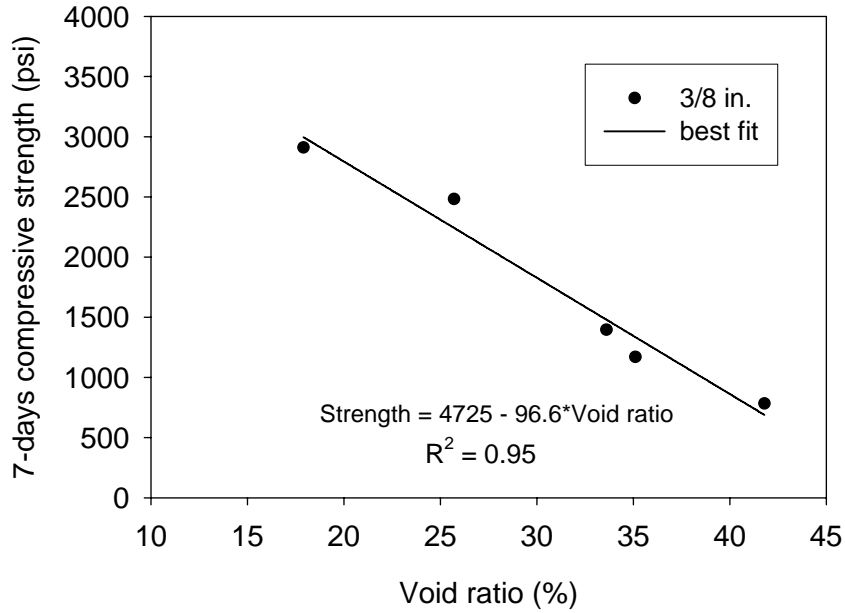
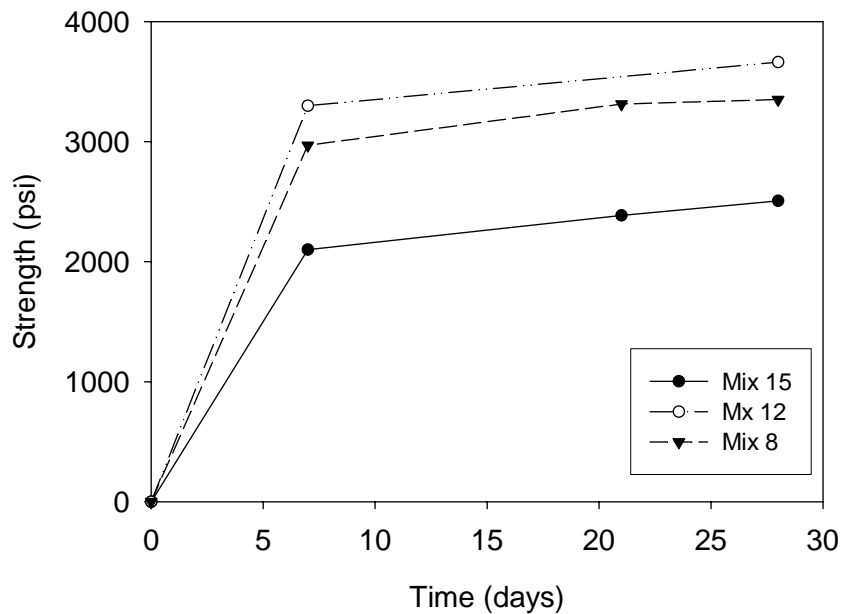


Figure 3. Seven-day strength as a function of void ratio for river gravel



**Figure 4. Seven-day strength as a function of void ratio for crushed limestone**

Figure 5 shows the development of compressive strength for three mixes with No. 4 river gravel as a function of time. Mix 15 is the basic mix with only aggregate. This figure shows that mix 12 (with aggregate and sand) has the highest strength. Furthermore, it is observed that using latex hindered the improvement of strength between 21 and 28 days for mix 8 (i.e., No. 4 river gravel with sand and latex). This shows that the addition of some sand and/or latex improves the strength of the mix above the aggregate-only mix.



**Figure 5. Strength increase as a function of time for No. 4 river gravel mixes**

## Void Ratio and Permeability

The permeability as a function of void ratio for all tested mixes is presented in Figure 6. This figure shows that permeability increases as the void ratio increases, with 20% void ratio being where the required strength of 3,000 psi was achieved (see Table 6).

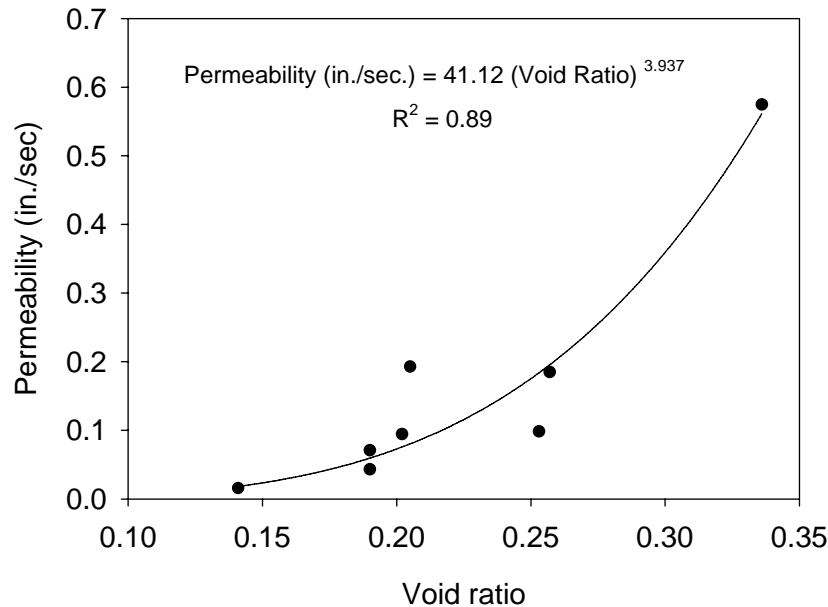
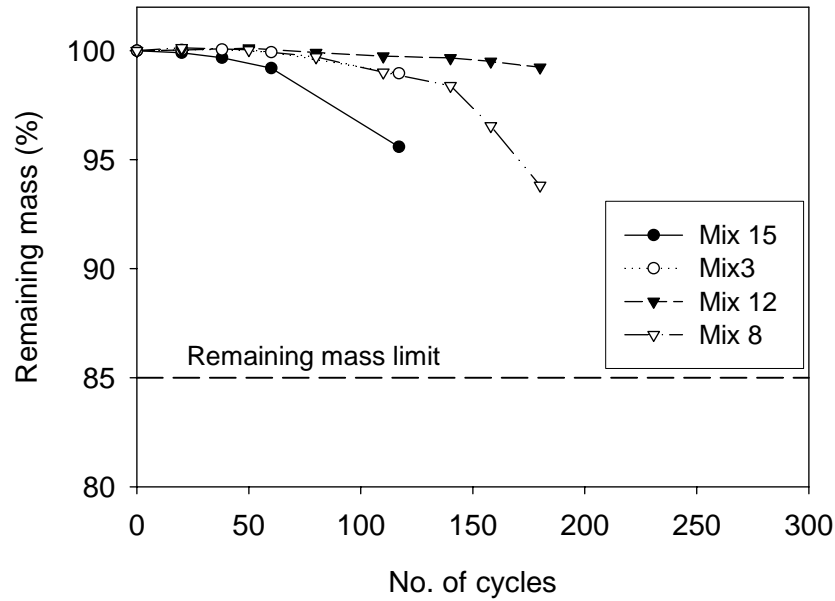


Figure 6. Change of strength and permeability as a function of void ratio

## Freeze-Thaw Durability

At the time of the preparation of this paper, mixes 8 and 12 have been subjected to 180 freeze-thaw cycles, while mixes 3 and 15 have been subjected to 117 freeze-thaw cycles, with no sample failing the weight loss criteria of 15% mass loss (see Figure 7). Test results of mix 8 with sand and latex show less freeze-thaw resistance than mix 12, where no latex was used. Latex has some inherent air entraining ability, but the samples containing a standard AEA were showing better freeze-thaw resistance than the sample relying on latex for air entrainment. Future latex mixes will include additional AEA that is currently used in the non-latex mixes. The majority of the mass loss is through the splitting of the aggregate with the river gravel, beginning this process after only a few cycles. The lower strength crushed limestone is showing better freeze-thaw resistance than expected, with mix 3 retaining more mass than either mix 15 at 117 cycles. To date, all mixes tested using freeze-thaw showed less than 6% mass loss.



**Figure 7. Freeze-thaw results to date**

## CONCLUSIONS

From this study the following conclusions can be made:

1. Mixes containing river gravel aggregate produced higher compressive strengths than those containing crushed limestone.
2. Although causing reductions in the void ratio, smaller aggregate provided concrete with higher strength.
3. The use of sand together with latex in a mix increased strength while decreasing void ratio and permeability.
4. The use of sand in a mix improved strength more than the use of sand together with latex.
5. Up to 180 cycles, mixes tested using freeze-thaw showed less than 6% mass loss.
6. Based upon the results to date, well-designed pervious concrete mixes can meet strength, permeability, and freeze-thaw resistance requirements for cold weather climates.

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