OPTIMIZING THE STRENGTH AND PERMEABILITY OF PERVIOUS CONCRETE

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ABSTRACT

This paper is focused on evaluating the performance of different pervious concrete mixtures in an endeavour to achieve an optimized mix with adequate tensile strength and porosity. In addition, a relationship was investigated between permeability and porosity of different mixtures. This is done in an attempt to use the porosity as a quick and easy quality control test for evaluating the permeability of pervious concrete. The mix design variables investigated in this study included aggregate-to-cementing materials ratio (A/CM), aggregate gradation and cementing materials blends; ternary blends of silica fume/slag and Metakaolin/Slag were examined. Single and hybrid fibre systems were also evaluated. These included Wollastonite natural fibres and polypropylene macro-fibres. Modifications to the permeability test proposed by ACI522R, "Pervious Concrete", were made to evaluate permeability of the specimens.

1 INTRODUCTION

1.1 OBJECTIVE

As our planet is faced with an environmentally uncertain future, a focus on green, sustainable development has become a necessity. Innovative concepts to our present infrastructure are currently being implemented, where Pervious Concrete Pavement (PCP) is among them. Operating on a "rain and drain" philosophy, PCP is able to collect the first-flush rainfall and allows it to drain immediately into the ground to recharge the water table. Due to its permeability requirement, PCP is typically designed with high void content and thus suffers from significantly reduced strength.

The primary aspiration of this research project is to optimize the strength of a PCP mix design without sacrificing permeability. The optimized blend of these parameters would improve bonding, thus reducing the effects of ravelling, while maintaining adequate permeability for drainage, and thereby allow the use of this unconventional concrete in a wider range of applications. To achieve this goal, blends of supplementary cementing materials (SCM) and hybrid systems of fibres are incorporated into the mix design to improve the properties of the Interfacial Transition Zone (ITZ) and enhance the tensile strength of the paste. The effects of SCM, fibres and aggregate gradations on strength and permeability were investigated.
A secondary target of this project was to investigate the relationship between the effective air voids and permeability, measured using an improved permeability test method. Overall, this resulted in a relationship between permeability and porosity.

1.2 PERVIOUS CONCRETE PAVEMENT (PCP)

PCP is a pioneering building material providing a wide range of not only environmental but also economic and structural advantages to take us one step further in the race for sustainable development and the preservation of our planet. Consisting of a combination of cementing materials, coarse aggregate, water, and a large void content in place of fine aggregate, PCP is currently ideal for walkways, courtyards, parking lots, and low-volume roads.

Operating on a "rain and drain" philosophy, PCP is able to collect the first-flush rainfall and allows it to drain immediately into the ground to recharge the water table. This eliminates the need for retention ponds, allowing for more efficient land development. Studies have shown that the hydrocarbons present in conventional asphalt oils are a source of nutrients to natural microorganisms; which are further decomposed and released into the atmosphere. PCP provides a structure which allows for runoff filtering of pollutants prior to penetration into the soil[1].

Air quality is also improved by lowering the heat island effect; a reduction of pavement temperature and ground level ozone[1]. PCP has been proven in freeze-thaw environments around the country and is also recognized as the best management practice when addressing pollution, runoff and erosion[1]. As its structure allows heat to be trapped, it causes snow and ice to melt, thus reducing dangerous road conditions. Consequently, the need for de-icing salts would be reduced.

Although PCP provides such a wide variety of desired characteristics, it has certain drawbacks that need to be addressed through further study of design and construction techniques. Due to its high voids content, PCP has relatively low strength and is also subjected to ravelling;[1] a key component of this project is to address this issue.

2 MATERIALS

Three different size fractions of crushed Limestone coarse aggregate were used in the study, namely 9-13 mm, 13-16 mm, and 16-19 mm. All aggregates were washed prior to mixing.

Type GU (10) Portland cement was used in the mixtures as the primary cementing material. In addition to the control mix, which contained 350kg of Portland cement per m^3 of concrete, mixtures containing different blends of Portland cement and supplementary cementing materials were also examined at a total cementing materials content of $350kg/m^3$.

A water-to-cementing material (W/CM) ratio of 0.27 was used is this study. Ratios of 0.27 to 0.30, with proper inclusion of admixtures, is standard procedure; ratios of 0.34 to 0.40 are also successful.[1] The 0.27 was used in this study to consider strength, permeability and void ratio [2] as excessive water will lead to drainage of the paste and therefore clogging of the pore system.[3] The absorption and moisture content of the aggregate on the day of mixing were determined and used to correct the mixing water.

Supplementary Cementitious Materials (SCMs) –SCMs have a large influence on the properties of concrete and are key to achieving high performance and sustainable mixes. Blends of the following SCMs were incorporated into various mix designs. Each blend contained two types of SCM adding up to 35% of the cementing materials. The GU Portland cement constitutes the remaining 65% of the total cementing materials.

Ground Granulated Blast Furnace Slag (GGBFS) – This by-product of iron and steel manufacturing adds strength and durability to concrete mixtures and can replace cement in quantities of 20-70%.[1] In this study, the mixtures contained 28% GGBFS which significantly reduced the carbon footprint of the final mix design.

Silica Fume (SF) –This by-product of silicone production consists of superfine spherical particles which significantly increase the strength and durability of concrete. It can replace cement in quantities of 5-12%.[4] Experimental studies have shown that the use of silica fume, in combination with high range water reducer (to make up for the workability reduction of SF), and smaller aggregate sizes, allows pervious concrete of both high strength and good water penetration to be produced.[5] In this study, some mixtures used 7% densified SF which further helps reduce the carbon footprint of the concrete mixture. The SF has a high capacity to consume calcium hydroxide and hence improves the ITZ around the aggregate. This is likely to contribute to the strength, especially at the presence of fibres, which enhances the strength of the paste and might leave the ITZ as the weakest part of the matrix.

Metakaolin – Metakaolin is a fine calcined clay powder that produces greater compressive strength values and rate when used in concrete. This is due to the pozzolanic reaction which significantly reduces the concentrations of ettringite and calcium hydroxide in the ITZ and produces more calcium silicate hydrate.

Fibres

Improvement of pervious concrete tensile strength can be achieved by improving the tensile resistance of the paste through the use of fibres. The mix optimization procedure considered stresses developed on both the macro and microscopic levels within the paste. The following fibres were implemented into the mix design:

Polypropylene Fibres – 19 mm-Polypropylene fibres were introduced into the paste to enhance the post-cracking behaviour of the paste. To ensure proper dispersion of these fibres, they were initially separated using an air compressor prior to mixing. The fibre was used at 2% by volume of concrete.

Wollastonite Natural Fibres – Focusing on tensile strength improvement, the addition of microfibers would help prevent cracking and resist stresses on the microscopic level. Two types of Wollastonite were used: (a) Ultra Fine Wollastonite (UF) with an average diameter and aspect ratio of 4 micron and 5 respectively; and (b) High Aspect Ratio (HAR) Wollastonite (as shown in Figure 1) with average diameter and aspect ratio of 75 µm and 20, respectively. Preventing these micro cracks was targeted as means to enhance tensile strength capacity of the samples.

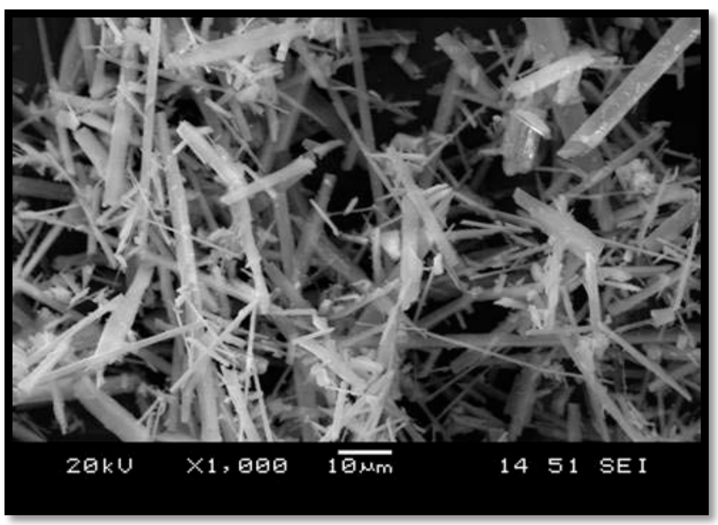

Figure 1 - Secondary Electron Image Showing Wollastonite HAR Fibres used in this Study

Chemical Admixtures _ As is the case in conventional concrete, chemical admixtures can be used in order to achieve important properties for pervious concrete:

Air Entraining – Use of air-entrainment is encouraged for pervious concrete in freeze-thaw susceptible environments to reduce free-thaw damage within the paste. In order to provide proper freeze-thaw resistance, the National Ready Mix Concrete Association (NRMCA) suggests achieving an air content of 4-8% with a minimum spacing factor of 0.254 mm.[1]

Water Reducing and Cement Dispersing –High Range Water Reducer (HRWR) was used to enable a low W/CM ratio and to aid in the dispersion of cementing material particles, especially silica fume. This is important in order to ensure proper strength of the paste and coating of the aggregate. This would create better bonding and improved strength.

3 MIXTURE PROPORTIONS AND MIXING PROCEDURE

The mixing procedures implemented in this study are outlined in this section, which follow Figure 2 below. This is a visual representation of the various procedures that took place in the mixing and batching stage.

Figure 2 - Mix Procedure

The following tables show various stages of mix design conducted to optimize particular parameters in each stage to achieve an optimal blend of strength and permeability. Results from each stage are presented in section 5.

MIX LEGEND

The following legends were developed to identify the different mixtures within the four stages in this study.

[S+M]: Portland Cement + Slag (S) at 25% + Metakaolin (M) at 10%
[S+SF]: Portland Cement + Slag (S) at 28% + Silica Fume (SF) at 7%
[Fibre]: [S+SF] + Polypropylene Fibre at 1.25% by volume of cementing materials
[Woll1]: [S+SF] + Wollastonite (Ultra Fine (4µm average particle size)) at 3% by volume of cementing materials
[Woll2]: [S+SF] + Wollastonite (75µm average diameter and 20 aspect ratio) at 3% by volume of cementing materials

Table 1 – Stage 1 of Mix Design Optimization

Stage 1: Nominal Size and A/CM Optimization - Dry Mass (kg/m^3)							
		1	2	3	4	5	6
Aggregate Size (mm)		10-13	10-13	13-16	13-16	16-19	16-19
A/CM		4	4.25	4	4.25	4.5	4.25
Ingredient							
Aggregate		1402	1490	1411	1490	1578	1490
Cement		350.0					
Water		102.3	103.4	93.38	103.4	104.5	103.4
Air Entrainment Admixture (mL/m^3)		333.3					
SP Admixture Optimization (mL/m^3)	Water Addition[1]	1417					
	Drum Addition[2]	83.33	416.6667	333.3	541.7	291.7	666.7

[1]added to mixing water
[2]added to drum in final stage of mixing to improve workability

Table 2 – Stage 2 of Mix Design Optimization

Stage 2: SCM Optimization - Dry Mass (kg/m^3)				
		1	2	3
Ingredient		13-16 mm		10-13 mm
		S+M	S+SF	
Aggregate		1411	1411	1414
Cement		227.5	227.5	
Slag		87.50	98.00	
Metakaolin		35.00	0.000	
Silica Fume		0.000	24.50	
Water		93.38		90.88
Air Entrainment Admixture (mL/m^3)		333.3		
SP Admixture Optimization (mL/m^3)	Water Addition	1417		1917
	Drum Addition	1250	1167	1250

Table 3 – Stage 3 of Mix Design Optimization

Stage 3: Fibre Reinforcement - Dry Mass (kg/m³)						
		1	2	3	4	5
Ingredient		13-16 mm			10-13 mm	
		Fibre	Woll1	Woll2	Fibre	Woll2
Aggregate		1411			1406	
Cement		227.5			227.5	
Slag		98.00			98.00	
Silica Fume		24.50			24.50	
Water		94.09			98.10	
Fibre		1.324	0.000		1.324	0.000
Wollastonite		0.000	10.55		0.000	10.55
Air Entrainment Admixture (mL/m³)		333.3				
SP Admixture Optimization (mL/m³)	Water Addition	1917			3333	4167
	Drum Addition	0.000	416.7	416.7	0.000	833.3

Table 4 – Stage 4 of Mix Design Optimization

Stage 4: Fibre Blending Optimization - Dry Mass (kg/m³)			
		1	2
Ingredient		13-16 mm	10-13 mm
		Fibre+Woll2	
Aggregate		1408	1406
Cement		227.5	
Slag		98.00	
Silica Fume		24.50	
Water		96.38	98.10
Fibre		1.324	
Wollastonite		10.55	
Air Entrainment Admixture (mL/m³)		333.3	
SP Admixture Optimization (mL/m³)	Water Addition	5000	
	Drum Addition	0.000	833.3

4 LABORATORY PROCEDURES

4.1 SPLITTING TENSILE STRENGTH

The indirect splitting tensile strength test was performed on specimens according to ASTM C496-96[6] using an MTS 815 machine. Three (3) cylinders were tested for each trial batch to obtain representation average and eliminate any outliers.

The load (P) was applied uniformly at a rate of 24.69 kN per second over the horizontally placed cylinder of length, L, and diameter, D. Ultimate loading capacity (f_c') was recorded and tensile strength was calculated in MPa, using the following formula:

$$f_c{}' = \frac{2P}{\pi L D} \qquad (1)$$

4.2 PERMEABILITY

Apparatus Design - Currently, there is no standardized method of measuring permeability for pervious concrete. A modification of the method outlined in ACI522R-06 was adopted to test the permeability of each sample.

A ‘permeameter’ has been constructed (as shown in Figure 3), which is composed of two parts; an encapsulating cylinder and flow pipe. An ultrasonic flow velocity meter is located at the base of the flow-generating pipe, which measures the flow in m/s with the use of clamp-on sensors that employ ultrasonic frequency technology injected transit-time method.

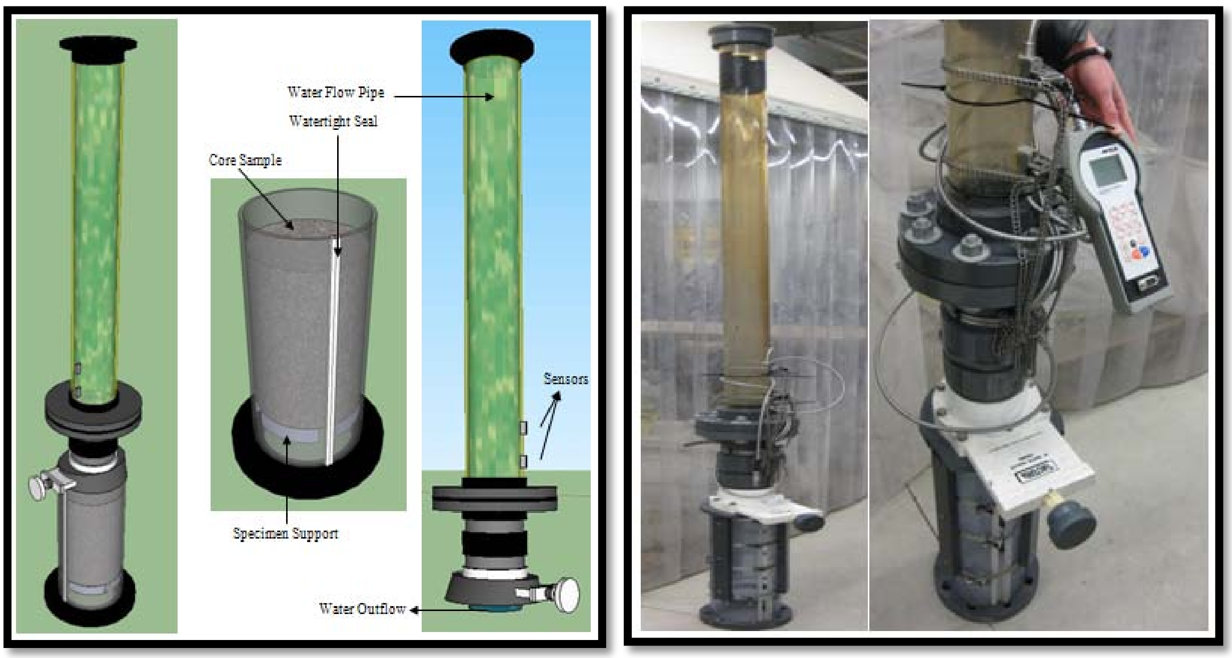

Figure 3 - Preliminary Apparatus and Hand-Held Device Sensors[9]

The transit-time meter relies on ultrasonic signals to travel along the pipe. The pipe must be free of air in order to avoid acoustic signal alterations.[7] Based on the preliminary laboratory results; an improvement to this apparatus was performed.

The mechanically operated valve was re-positioned below the specimen (Figure 4), such that it becomes fully saturated. This provided a ‘bubble relief’ system located at the sensors’ position. It also included a rubber membrane that encases the concrete specimen, situated within a pressurized chamber, which ensured that the water flows through the specimen as opposed to the sides of an encapsulating cylinder as per the original design. This modification eliminates leakage along the side of the specimens. A constant air pressure of 30 psi is exerted onto the membrane which conforms to the specimen.

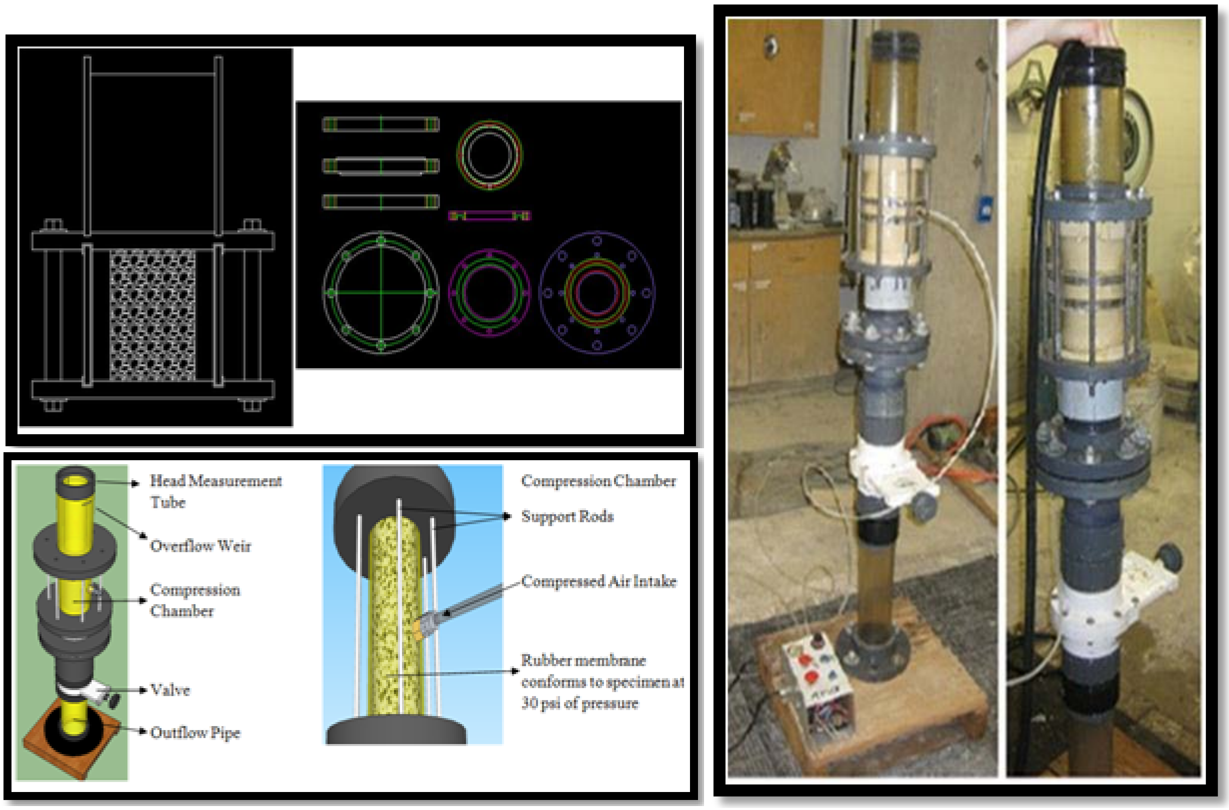

Figure 4 – Final Apparatus Modifications with Overall Configuration and Compression Chamber

Apparatus Operation - Major modifications to the apparatus allowed for much more efficient operation and accurate results. Positioning the valve underneath the specimen creates full initial saturation, allows all air bubbles to escape, and eliminates the initial spike in flow upon opening the valve. The starting point water level is constant and repeatable since there is a weir slot machined into the water column cylinder. The column was filled to the overflow weir slot to a height of nine (9) inches. The duration of water flow was recorded for the water height to drop from 9 to 5 inches.

4.3 POROSITY

Both bulk volume of the sample and volume of solids (stone and cementing materials) were determined and used to calculate porosity using the following equation:

$$\text{Porosity (\%)} = \frac{Volume\ \ of\ Pores\ (L)}{Bulk\ Volume\ \ (L)} \times 100 \qquad (2)$$

Volume of solids was the difference between the mass of the sample in air minus the mass of the sample submerged in water. All tested specimens were cut by an inch from each end to ensure consistency in specimens' porosity by removing the top and bottom portions of the cylinder sample.

Figure 5 – Porosity Testing

Figure 6 - Laboratory Testing Procedures

5 EXPERIMENTAL PROGRESS

5.1 NOMINAL SIZE AND A/CM OPTIMIZATION

The objective of this first set of test batches was to determine the optimal aggregate size and A/CM ratio strictly based on tensile strength results. As shown in Table 5, the 13-16 mm gradation, with an A/CM ratio of 4, provided the best results. It was decided to use an A/CM ratio of 4 in stage 2 to investigate both 13-16 mm and 10-13 mm aggregate. The 10-13 mm aggregate size was included in further stages as it was believed that the performance of this aggregate size might be significantly enhanced when fibres are incorporated in the mixtures (Stages 3 and 4).

Table 5 – Stage 1 Tensile Strength

	Stage 1: Nominal Size and A/CM Optimization			
	Stage 1*		7-Day Tensile Strength (MPa)	
	Aggregate Gradation (mm)	A/CM	Average	Standard Deviation (3 specimens)
1	10-13	4	0.7506	0.06662
2	10-13	4.25	0.6967	0.4131
3	13-16	4	1.156	0.1495
4	13-16	4.25	0.8953	0.08512
5	16-19	4.5	0.7786	0.1803
6	16-19	4.25	0.6155	0.1311

* No permeability recordings were conducted for Stage 1

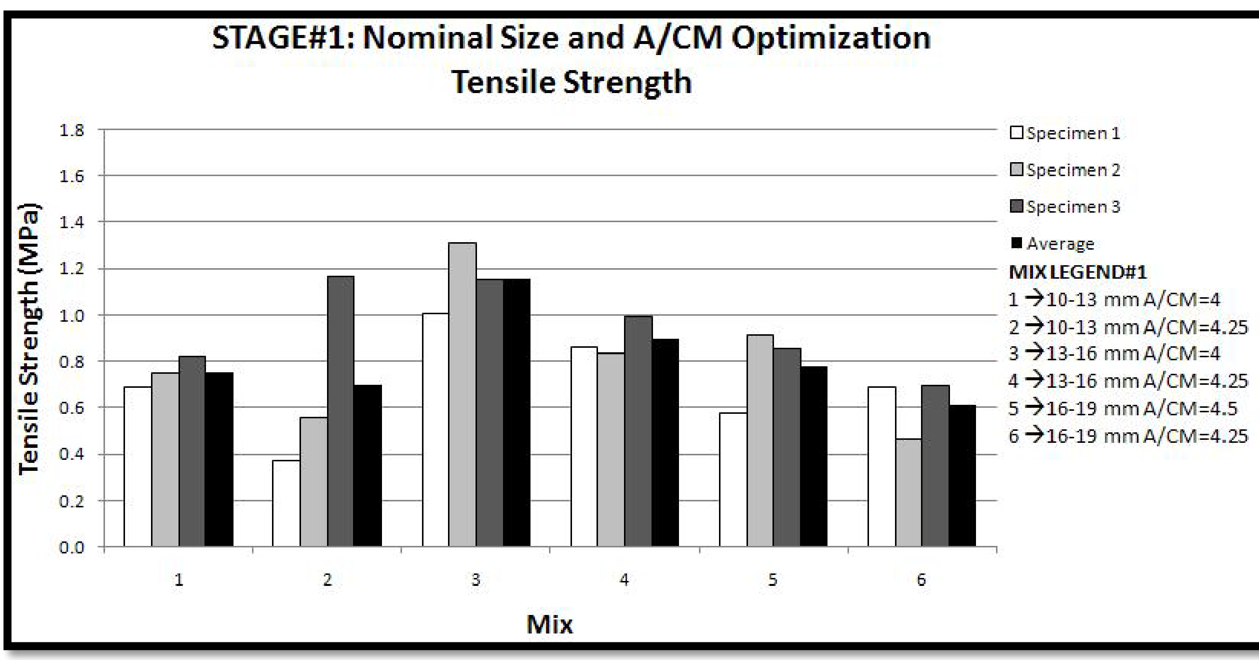

Figure 7 – Stage 1: 7-Day Tensile Strength Testing Results

5.2 SUPPLEMENTARY CEMENTATIOUS MATERIAL OPTIMIZATION

Two different ternary blends were investigated: (a) slag and silica fume; and (b) slag and Metakaolin. In both systems, the Portland cement was used as the third cementing component. These two blends were investigated with aggregate size of 13-16 mm. In addition, the slag and silica fume was also investigated with 10-13 mm aggregate. As the graph in Figure 8 shows, both (S+M) and (S+SF) blends used with 13-16 mm aggregate obtained similar results in terms of average strength and permeability. The (S+SF) was selected for the following stages of the program. In addition, the same blend used with 10-13 mm aggregate was also investigated in the following stages to examine the performance of this mix when fibres are incorporated.

Table 6 – Stage 2 Testing Results

		Stage 2: SCM Optimization					
		7-Day Tensile Strength (MPa)		Permeability (mm/s)		Porosity (%)	
Stage 2		Average	Std. Deviation (3 specimens)	Average	Std. Deviation (3 specimens)	Average	Std. Deviation (3 specimens)
1	13-16 mm S+M	1.097	0.3373	13.81	0.9832	25.41	1.143
2	13-16 mm S+SF	1.150	0.4103	12.89	1.394	23.47	0.3134
3	10-13 mm S+SF	0.8479	0.09422	22.96	4.078	31.83	0.5050

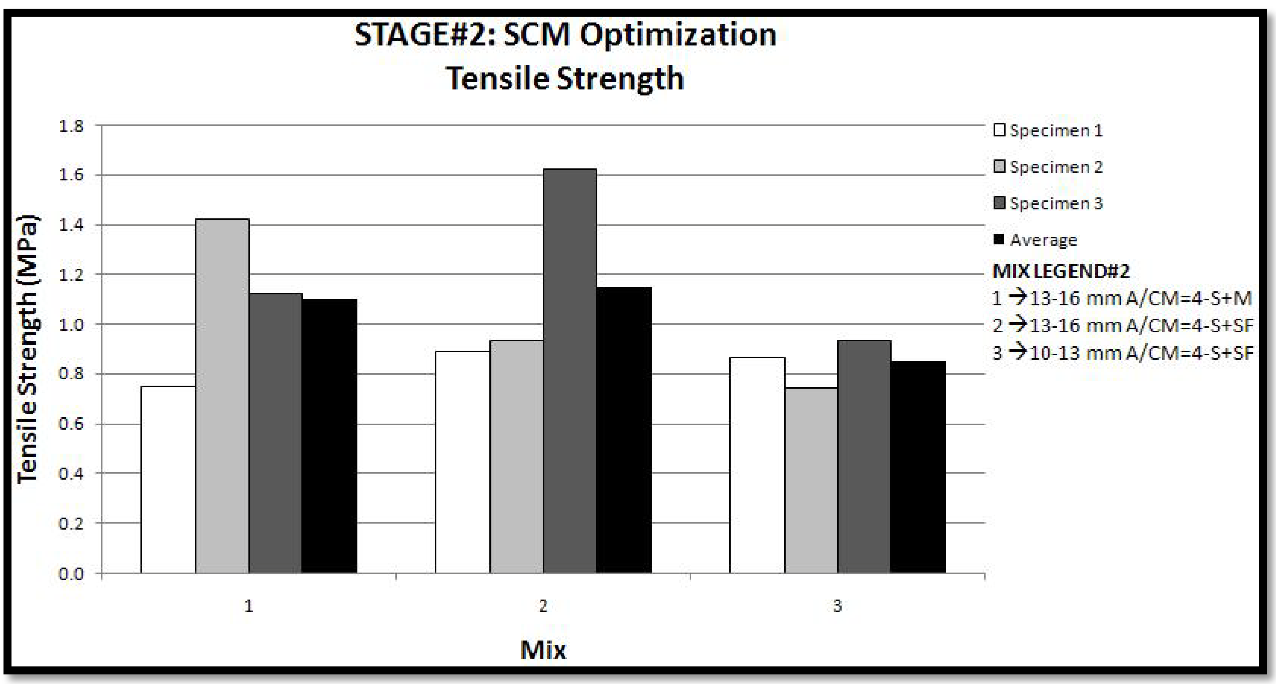

Figure 8 - Stage 2: 7-Day Tensile Strength Testing Results

5.3 FIBRE REINFORCEMENT

The third stage incorporated the addition of one type of fibre, either Polypropylene or Wollastonite, to the ternary blend. Two forms of Wollastonite were tested, Woll1 (Ultra Fine, UF) and Woll2 (High Aspect Ratio, HAR). As shown in Table 7, the HAR form of Wollastonite yielded better results.

Table 7 – Stage 3 Testing Results

Stage 3		Stage 3: Fibre Reinforcement					
		7-Day Tensile Strength (MPa)		Permeability (mm/s)		Porosity (%)	
		Average	Std. Deviation (3 specimens)	Average	Std. Deviation (3 specimens)	Average	Std. Deviation (3 specimens)
1	13-16 mm Fibre	0.9042	0.09861	15.85	1.088	29.67	1.188
2	13-16 mm Woll1	0.4934	0.1076	24.37	1.022	33.73	1.163
3	13-16 mm Woll2	0.6507	0.1540	21.39	0.5687	31.02	0.07371
4	10-13 mm Fibre	1.360	0.1302	12.66	2.168	24.30	1.002
5	10-13 mm Woll2	1.055	0.2333	16.15	1.317	25.52	1.141

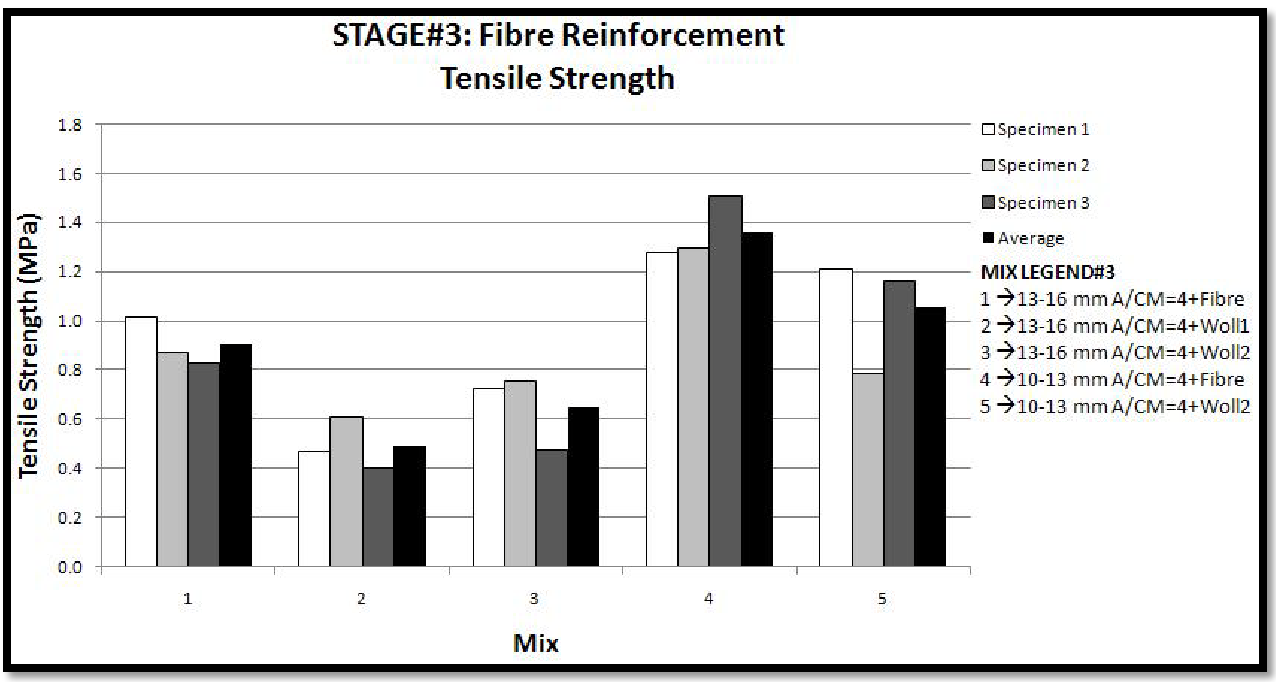

Figure 9 - Stage 3: 7-Day Tensile Strength Testing Results

5.4 FIBRE BLENDS

Finally, the two aggregate sizes, 13-16 mm and 10-13 mm, were tested with a blend of HAR Wollastonite and polypropylene fibres. The results are presented in Figure 10 which shows the 13-16 mm to produce higher porosity and lower strength while 10-13 mm aggregate produced low porosity and high strength. Ultimately, the sacrifice of permeability of the 10-13 mm samples was insignificant compared to the achieved tensile strength. Indeed the porosity of the sample with 10-13mm aggregate was within the recommended level of porosity for pervious concrete.[3]

Table 8 – Stage 4 Testing Results

Stage 4		Stage 4: Fibre Blending Optimization					
		7-Day Tensile Strength (MPa)		Permeability (mm/s)		Porosity (%)	
		Average	Std. Deviation (3 specimens)	Average	Std. Deviation (3 specimens)	Average	Std .Deviation (3 specimens)
1	13-16 mm Fibre+Woll2	0.9070	0.09490	20.55	0.5770	30.07	1.002
2	**10-13 mm Fibre+Woll2**	**1.467**	**0.2958**	**13.71**	**1.872**	**24.10**	**1.580**

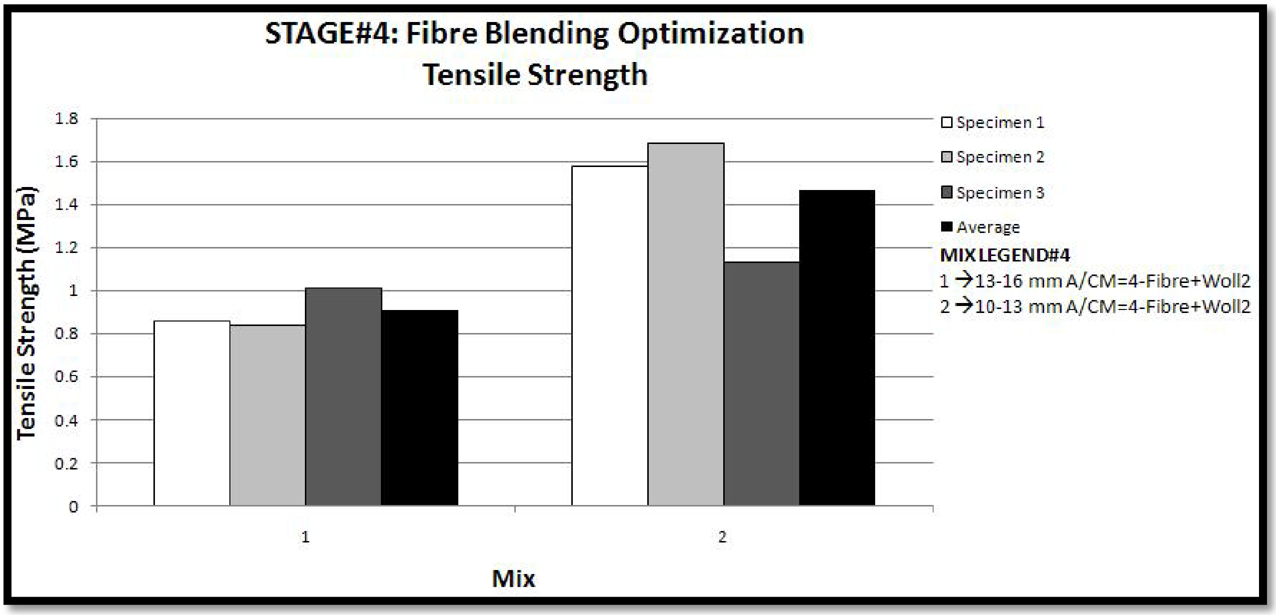

Figure 10 – Stage 4: 7-Day Tensile Strength Testing Results

6 DISCUSSION

6.1 PERMEABILITY VERSUS POROSITY

Figure 11 shows a linear regression between permeability and porosity. The relationship should be investigated further with a wider range of materials. However, the graph shows that a similar but more representative relationship can be used to predict permeability of pervious concrete based on the measured porosity. Since permeability is one of the main properties of pervious concrete, it is imperative to find a fast and reliable quality control approach to assess it. Determining the porosity of samples could be one of such approaches.

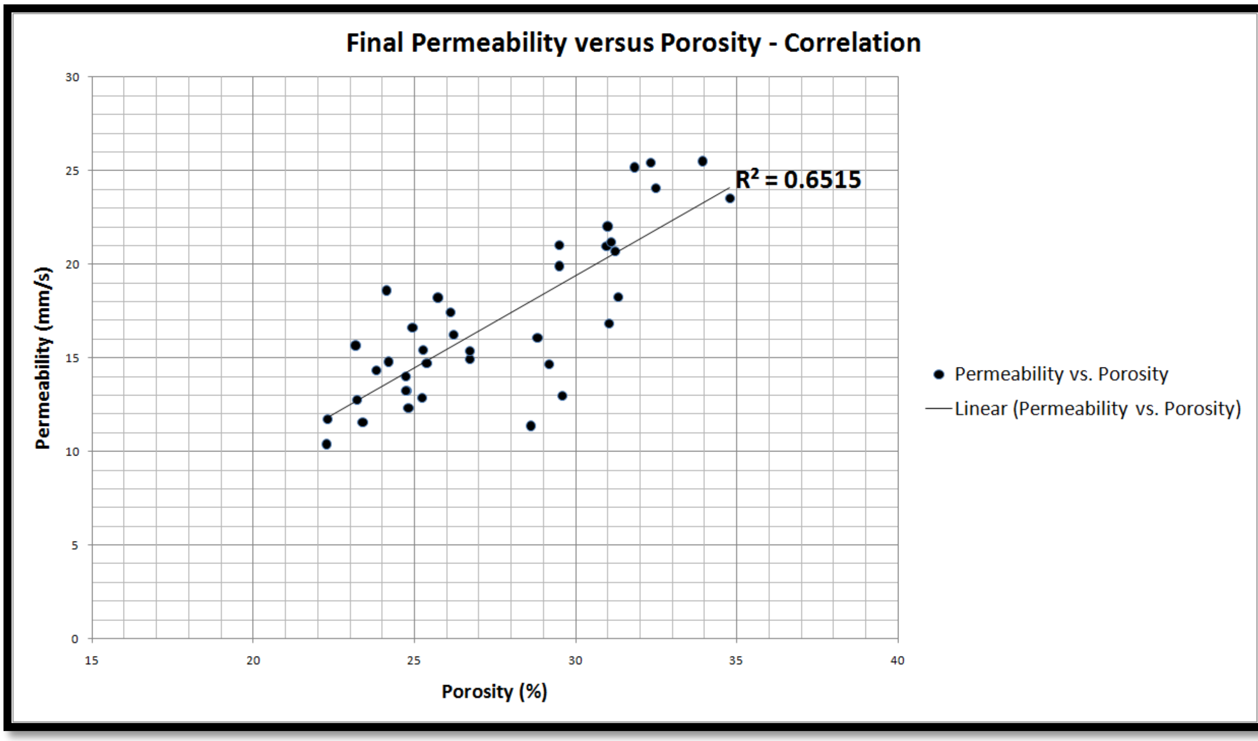

Figure 11 - Permeability versus Porosity

6.2 TENSILE STRENGTH VERSUS PERMEABILITY

Tensile strength acted as the key factor for determining optimal proceeding mix design. If no significant change in permeability was observed, the mixtures for the following step were selected based on tensile strength.

At stage 2 of the mix optimization, as shown in Figure 12, the mix with aggregate gradation of 13-16 mm with Metakaolin was eliminated, partly, due to higher test variability within the tested specimens, compared to the S+SF blends.

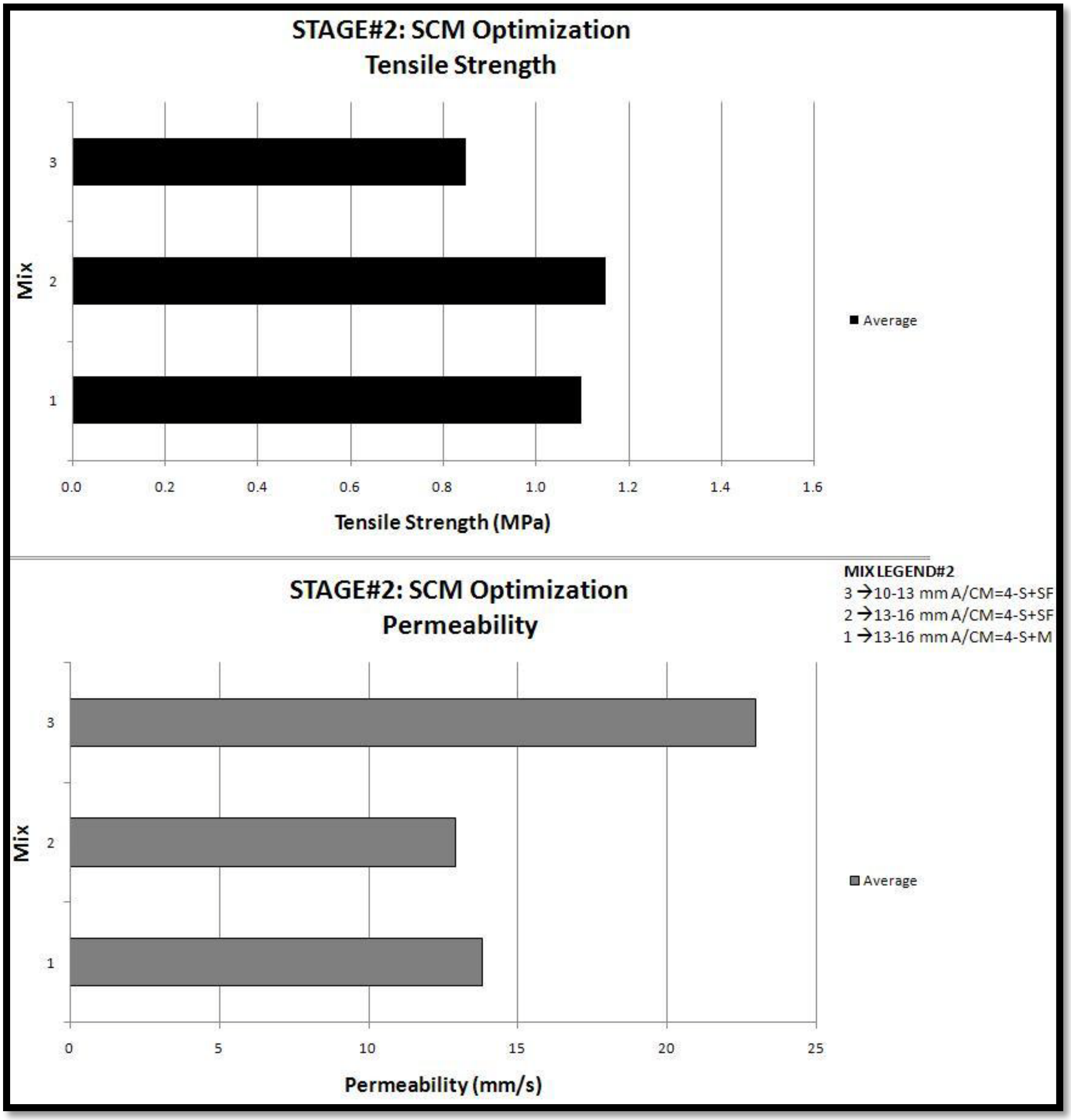

Figure 12 – Stage 2 Tensile versus Permeability

At stage 3, the mixes with silica fume and slag in both 10-13mm and 13-16mm aggregate gradation were tested with the fibre addition. As shown in Figure 13, mix 4, with 10-13mm aggregates and fibres, achieved the highest tensile strength as well as the lowest permeability. However, the porosity value for this sample was 24% which is still within the acceptable range of porosity for pervious concrete. In addition, some samples showed higher than the recommended range. While high porosity is good for permeability, very high porosity (>26%) is likely to be associated with weak concrete that is susceptible to ravelling (aggregate loss).[3]

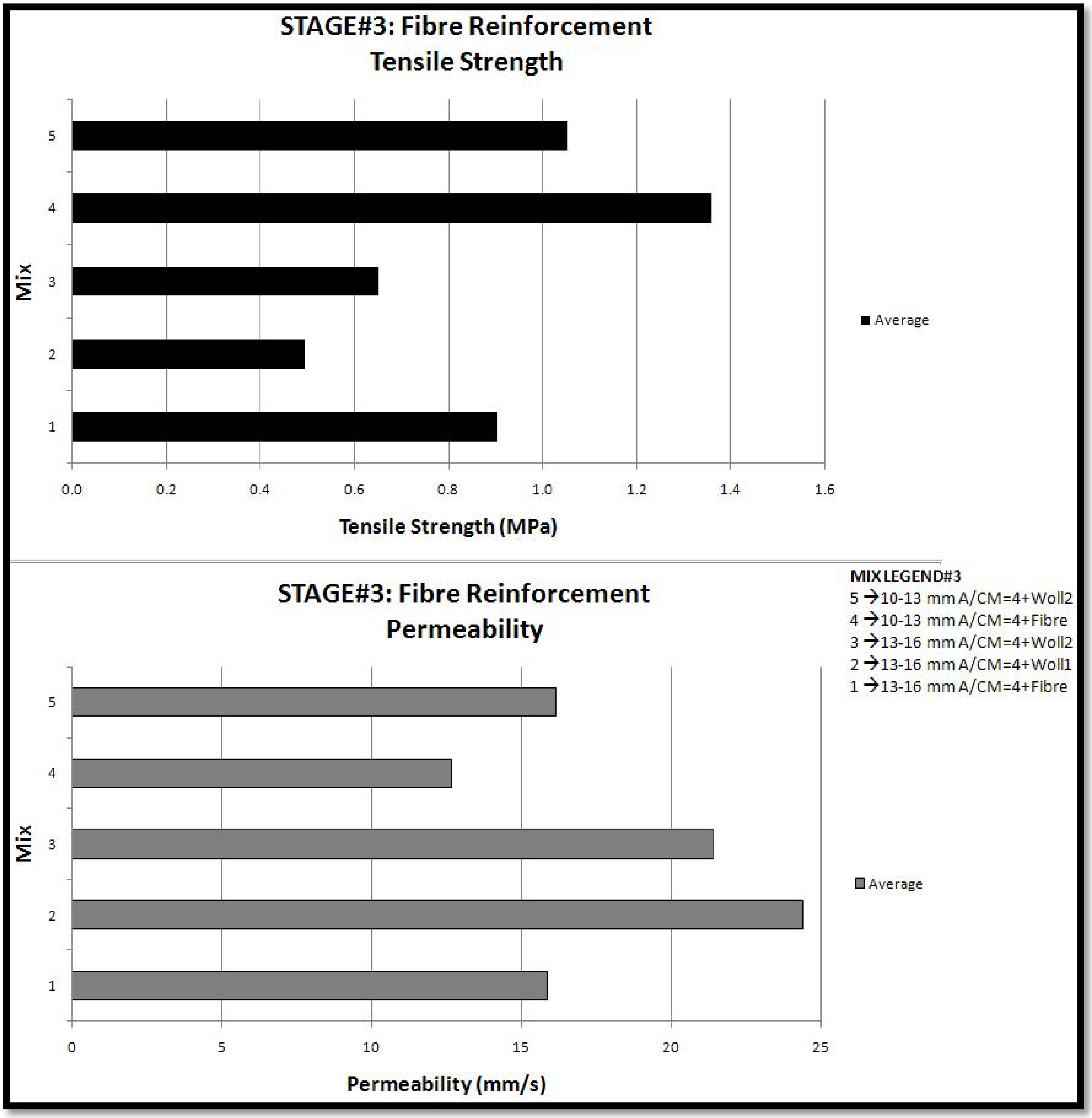

Figure 13 – Stage 3 Tensile Strength versus Permeability

The permeability decreases with a decrease in aggregate size and the addition of SCMs, as well as fibre addition. As long as permeability was obtained within values recommended by ACI522R-06, factors increasing the tensile strength properties were considered in the following stage of the mixture selection.

The UF Wollastonite did not show any improvement in the strength. This is attributable to the high finesse and low aspect ratio. This was not the case with the HAR Wollastonite which showed improvement in strength.

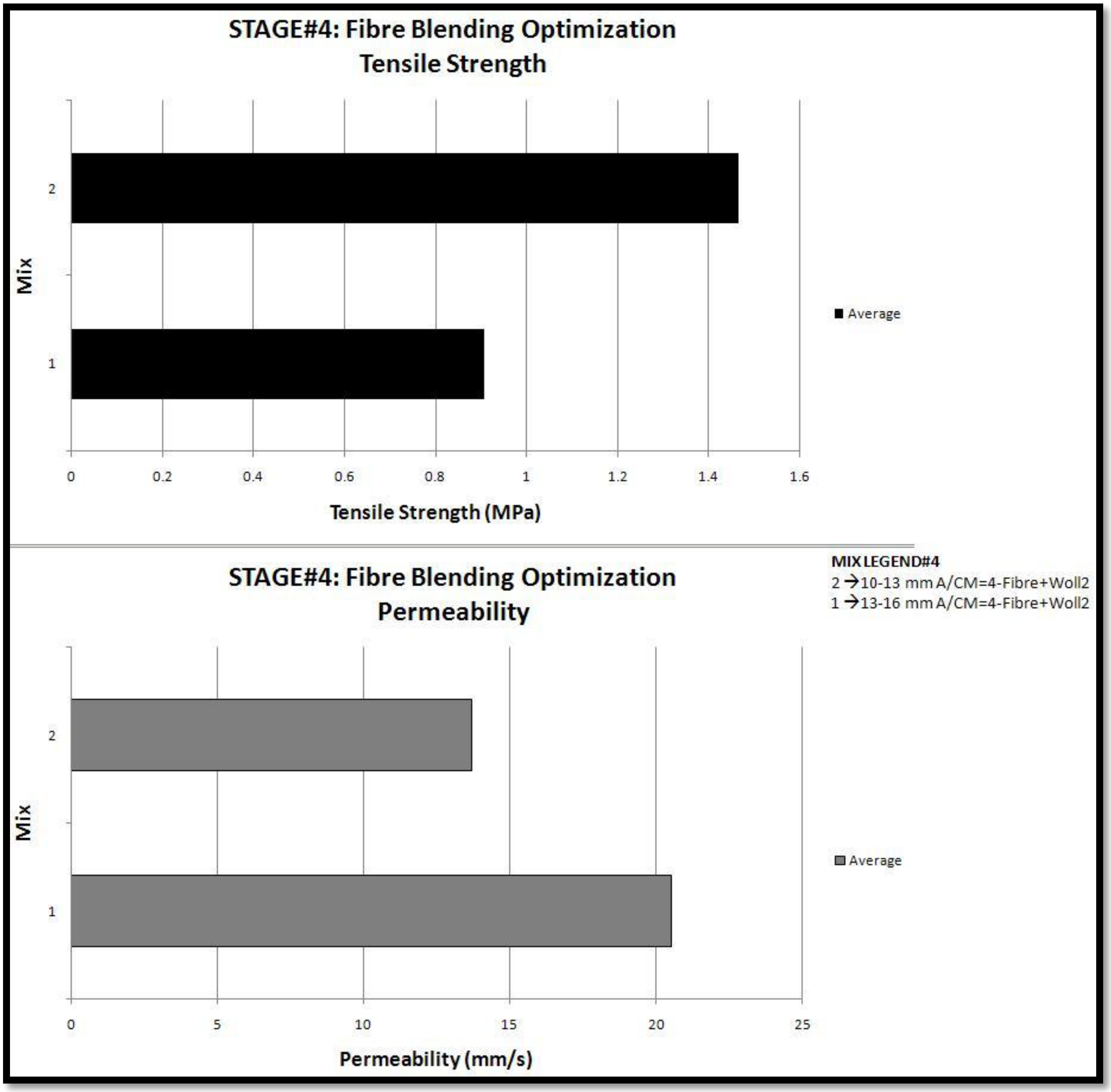

Figure 14 – Stage 4 Tensile Strength versus Permeability

It was also observed that both HAR Wollastonite and Polypropylene fibres performed better when used with 10-13mm aggregate compared to the performance when used with 13-16mm aggregate. It was also assumed that, when both HAR Wollastonite and Polypropylene fibres are used together, a synergetic effect would be achieved. This is because it is believed that one would work on the microscopic level (Wollastonite) and the other on the macroscopic level (Polypropylene). Indeed, the results showed this to be the case.

7 CONCLUSIONS AND RECOMMENDATIONS

1) An optimized pervious concrete mix was achieved using aggregate size of 10-13mm, an A/CM ratio of 4, and a ternary cementing blend of silica fume and slag.

2) Upon study of the failure plane, it was found that splitting occurs along the paste rather than through the aggregates. Testing of tensile strength revealed that the addition of Wollastonite and polypropylene fibres improved the strength of the paste.

3) A correlation factor of 0.65 was attained for permeability when plotted against porosity. It is recommended to further investigate this relationship using different mixtures.

4) Further improvement of tensile properties should be investigated by conducting trials using a variety of fibre contents. As the paste composition was optimized, it is recommended to utilize higher quality aggregate in order to withstand these higher stresses.

5) Sustainable development can be achieved in PCP through the implementation of fibres and various SCMs to accomplish better strength and permeability. To improve the sustainability of mixtures in areas where slag is not readily available, testing should be performed using fly ash.

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