Engineering Properties and Hydraulic Characteristics of Cement Kiln Dust Modified Pervious Concrete

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Abstract:

Pervious pavements provide a vital solution to urban environmental engineering issues through their ability to reduce stormwater runoff and improve water quality. Pervious concrete, the most commonly used material in pervious pavements, uses almost the same materials as traditional concrete except the fines are eliminated allowing for minimal particle packing. Although pervious concrete has been used successfully in many countries for the past 30 years, the amount of CO_2 released to the atmosphere (5% of global manmade CO_2 emissions) during cement production is a major concern of both the scientific and engineering communities. There is a need for alternative, sustainable materials that perform at the same levels as current materials.

This study assessed the properties of modified pervious concrete containing cement kiln dust (CKD). Cylindrical specimens were prepared using various ratios of aggregate to cement (A/C, by weight), water to cement (w/c) and CKD to cement (CKD/C). The specimens were then tested for hydraulic conductivity and strength. Results showed an inverse relationship between hydraulic conductivity and CKD/C ratio and a direct relationship between indirect tensile strength and CKD/C. The hydraulic conductivity and strength values of specimens were within the expected values found in the literature for porous materials. This work not only produced a new class of sustainable durable materials, but also recycled a large quantity of industrial waste that was otherwise sent to landfills.

Introduction

Lebanon is one of many countries experiencing water stress due to urbanization. Increased stormwater runoff and the proportion of impervious surfaces which prevent precipitation from percolating into the ground are directly related to urbanization. Using pervious concrete could present an excellent, economical solution to groundwater depletion in Lebanon.

Pervious concrete pavement provides a sustainable solution to the critical environmental issue of stormwater runoff. They reduce stormwater runoff by allowing it to infiltrate into the ground, replenishing underground aquifers. The storage capacity of the sub-base layer of pervious pavement is considered an excellent method for eliminating the need for retention ponds, which will lead to more efficient use of land in a country where property value is steadily rising. Studies have shown that pervious pavements also reduce the level of pollution contained in stormwater runoff by allowing the percolation of water into the ground. Pervious concrete pavement with blended cement kiln dust (CKD) is an improved mixture which offers economic, environmental and structural advantages. The use of waste material in concrete pavement development is part of the sustainable development and preservation of available resources. This study evaluated the permeability and strength of pervious cement mixes using CKD.

Background

The concrete pavement industry is becoming more innovative and competitive. At the same time the negative environmental impacts of cement production are increasing. We can take advantage of concrete's versatility to create pavements that are functional, economic and meet environmental and social needs. Use of sustainable concrete pavement is good engineering practice as it involves working with limited resources to achieve the best possible product (Thomas and Peter, 2009). Using a sustainability approach for concrete mixtures will promote concrete as a pavement material by reducing negative environmental impact and lowering the cost of concrete pervious blocks and mixes (Wathne, 2008).

Yada et al. (2011) studied the manufacture and hydraulic and mechanical properties of a porous plastic-based cementitious (P-PBC) material. P-PBC, produced from plastic waste, soil and aggregates, offers an effective technique for reducing stormwater runoff, improving water quality and providing a structural pavement suitable for pedestrian and vehicular loadings. It also helps divert a large amount of plastic from landfills and incinerators thus playing a crucial role in the recycling program currently underway. Findings showed that *k* and indirect tensile strength test (ITS) values of specimens were within the expected values found in the literature for porous pavements. It was also found that the *k* values decreased with the amount of plastic waste. ITS increased with the amount of plastic waste. In addition, findings indicated that P-PBC could be an effective Stormwater Best Management Practice with significant positive economic and ecological implications.

McCain and Dewoolkar (2010) studied the mechanical and hydraulic characteristics of pervious concrete by varying the size of the specimens and the water-cement ratios. Results showed that the water-cement ratio had a significant effect on the density, strength and hydraulic conductivity of the specimens (i.e., as the water-cement ratio increased the density and strength increased while the hydraulic conductivity decreased).

Delatte et al. (2009) assessed the performance of pervious concrete in the laboratory and field. Pervious concrete specimens were tested for void ratio, hydraulic conductivity, compressive strength, and tensile strength. Field evaluation methods included visual inspection, two surface drainage measurements, and an indirect-transmission ultrasonic pulse velocity (UPV) test. Other pertinent information on pervious concrete pavement is given in Huang et al. (2010), Henderson et al. (2009), Haselbach (2009), Rizvi et al. (2009) and Tennis et al. (2004).

Poulikakos and Partl (2009) evaluated the effect of moisture susceptibility on porous asphalt specimens. Specimens were subjected to wet and dry conditions and then tested for ITS and coaxial shear tests (CAST). Results showed that ITS and CAST decreased noticeably when the specimen was immersed in water. Rungruangvirojn and Kanitpong (2009) measured visibility loss due to splash and spray for three different pavements: porous asphalt (PA), stone mastic asphalt (SMA) and conventional dense graded asphalt pavement. Two different methods were used to measure visibility loss: light reduction method (LMR) and color changing method (CCM). The results showed that the type of pavement effects visibility; the loss of visibility was 1.4 times higher on conventional dense graded asphalt pavement compared to SMA and PA.

Materials

Three materials were used to prepare pervious concrete specimens: Portland cement, CKD and limestone aggregates. Portland cement was provided by the "Factory Cementrie national (Al Sabeh)" cement factory. CKD is a solid waste created when clinker is formed during the third stage of manufacturing Portland cement using the dry process. The CKD used in this study was purchased from HOLDERCHEM Building Chemicals. It was added as a percentage by mass of Portland cement to some of the mixes to make it more sustainable and cost efficient. The aggregates were obtained from the quarries in Mairouba, Mount Lebanon. The actual gradation used was based on the ASTM C33 No. 8 gradation, as shown in Figure 1.

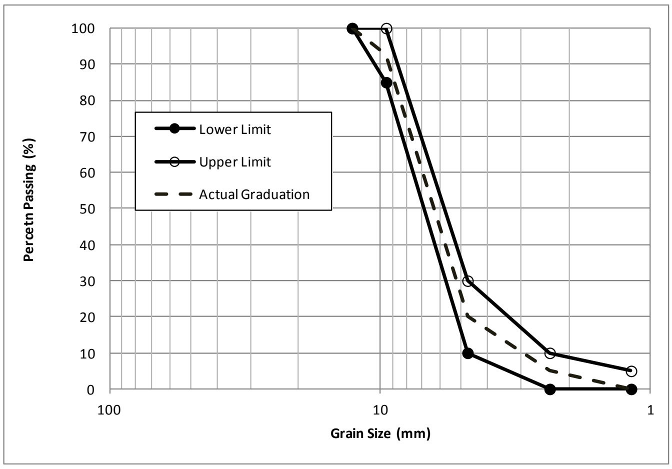

Figure 1 – Gradation

Specimen Preparation

A sieve analysis using a mechanical shaker was performed on the aggregates using sieves with openings 12.5, 9.5, 4.75, 2.36 and 1.18 mm. After removing the sieves, the desired gradations were obtained by weighing out the appropriate amount of each grain size. The proportions of cement, water and CKD utilized in the mixture were as follows:

(1) Aggregate to cement ratios (A/C) of 3.75:1, 4:1, 4.25:1, and 4.5:1.
(2) Water to cement ratios (w/c) of 0.33, 0.36, 0.39, and 0.42.
(3) Cement Kiln Dust (CKD) proportions of 0, 5, 10 and 15%.

Specimens were mixed manually and water was slowly added to ensure equal distribution throughout the mix. The mixtures were put in cylinders with diameters of 15 cm and heights of 5 cm by applying standard rodding for compaction and then left to cure for seven days. After curing, specimens were conditioned in water for 24 hours prior to any laboratory testing. More than 80 specimens with different mixtures and material proportions were prepared with three replicates of each specimen mixture.

Laboratory Testing

A permeameter was built; refer to Figures 2 and 3, in order to test the permeability of the pervious concrete specimens according to the falling head approach. Permeability tests were performed according to Fwa et al. (1998). The procedure was as follows: (1) place a membrane around a specimen; (2) apply a pressure of 5 psi between the sample holder and membrane, thereby eliminating the water flow between the sample holder and specimen; (3) apply a water head of 50 cm; (4) record the water drop with time; (5) plot the discharge rate with hydraulic gradient; (6) fit the laboratory data to the modified Darcy's equation (Eqn.1) to determine permeability.

Figure 2 – Permeameter Setup

Figure 3 - Membrane Before and After Pressure Application

$$v = k\ x\ i^n \qquad \text{Eqn. (1)}$$

Where, v = discharge velocity (cm/s)

k = hydraulic conductivity (cm/s)

i = hydraulic gradient (dimensionless)

n = turbulence coefficient (1 for laminar flow, approximately 0.5 for turbulent flow)

Figure 4 illustrates the discharge rate as a function of the hydraulic gradient for the data taken from the average of the three trials for a selected specimen. Indirect tensile tests were conducted in accordance with the ASTM C 6931-07 test methods. A laboratory procedure described in Somer and Winner (1998) was used to determine the porosity of specimens.

Presentation and Discussion of Results

Permeability

Figure 5 shows a plot of permeability versus void ratio (e). As the permeability increased (from 0.12 cm/s to 1.35 cm/s) the void ratio also increased (from 0.16 to 0.46). Figure 6 shows that permeability values varied from one w/c ratio to another due to different A/C ratios and CKD proportions. For w/c = 0.36, permeability of pervious concrete ranged from

0.79 to 1.35, for w/c = 0.39 permeability ranged from 0.25 to 0.95 and for w/c = 0.42 it ranged from 0.12 to 0.45. It can be concluded that permeability decreased with an increased water to cement ratio, as shown in Figure 6 and Table 1.

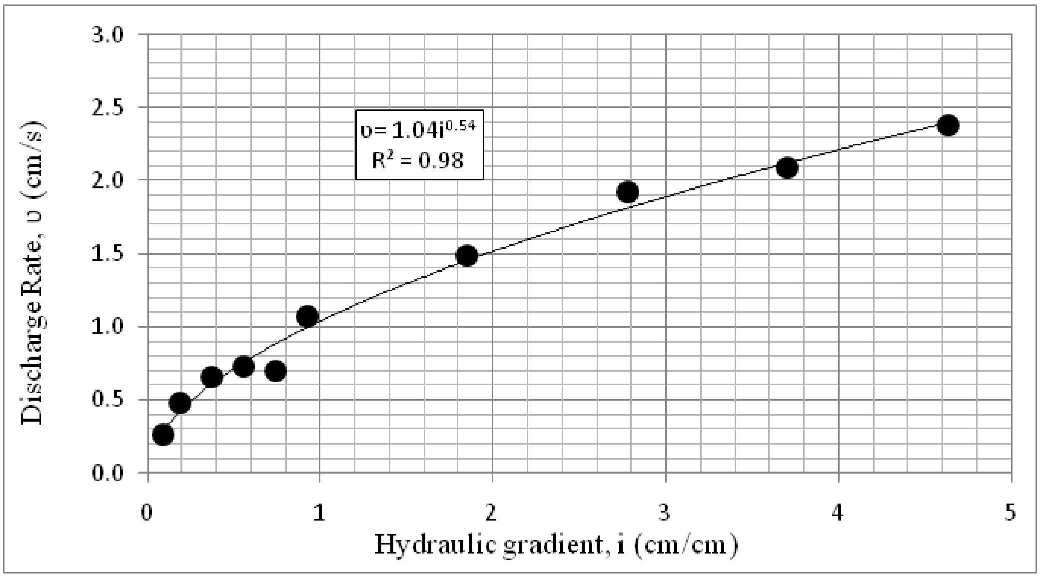

Figure 4 - Average Value Data Plot (Selective Specimen)

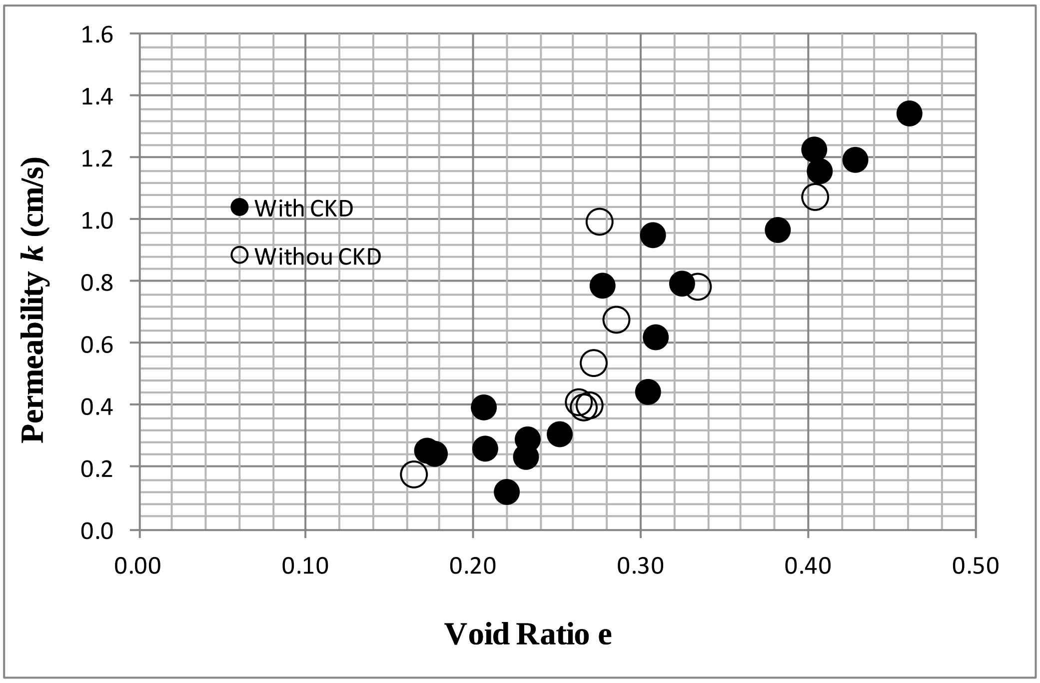

Figure 5 - Permeability vs. Void Ratio Plot

Table 1 - Test Matrix

	A/(C+CKD)	W/(C+CKD)	CKD/C	Void Ratio (e)	Stdev[1] (e)	K[2]	Stdev k	COV K	γ[3]	Stdev γ	COV γ	ITS[4]	Stdev ITS	COV[5] ITS
With CKD	4.00	0.36	0.05	0.46	0.01	1.35	0.08	6.18	16.53	0.11	0.65	1056	34.70	3.29
			0.10	0.40	0.08	1.23	0.23	18.32	17.15	0.88	5.13	1049	134.25	12.80
			0.15	0.43	0.03	1.20	0.06	4.60	16.68	0.20	1.23	785	38.07	4.85
		0.39	0.05	0.21	0.14	0.40	0.35	89.14	18.41	0.99	5.38	1574	118.97	7.56
			0.10	0.32	0.19	0.80	0.52	65.09	17.69	0.49	2.78	1015	217.23	21.41
			0.15	0.31	0.18	0.95	0.12	12.69	17.85	0.40	2.24	1185	232.72	19.64
		0.42	0.05	0.25	0.15	0.31	0.10	30.77	18.69	0.54	2.91	1532	195.65	12.77
			0.10	0.21	0.14	0.26	0.03	12.21	19.40	0.64	3.32	1656	192.24	11.61
			0.15	0.30	0.18	0.45	0.20	44.46	18.65	1.14	6.14	1484	230.88	15.56
	3.75	0.36	0.05	0.41	0.03	1.16	0.13	10.80	17.21	0.53	3.08	990	66.89	6.76
			0.10	0.38	0.04	0.97	0.16	16.37	17.28	0.44	2.57	893	95.53	10.70
			0.15	0.28	0.03	0.79	0.20	24.93	18.06	0.51	2.85	1060	227.42	21.46
		0.39	0.05	0.31	0.01	0.62	0.10	15.83	17.75	0.18	1.01	794	166.68	20.98
			0.10	0.18	0.02	0.25	0.05	19.16	19.52	0.34	1.77	1529	214.57	14.04
			0.15	0.17	0.02	0.26	0.18	71.98	19.54	0.27	1.41	1521	142.49	9.37
		0.42	0.05	0.22	0.06	0.12	0.06	47.51	19.11	0.97	5.09	1724	88.65	5.14
			0.10	0.23	0.03	0.24	0.07	29.68	18.92	0.52	2.74	1588	258.65	16.29
			0.15	0.23	0.02	0.29	0.11	37.55	18.74	0.29	1.54	1210	135.58	11.21
Without CKD	4.00	0.36	0	0.33	0.05	0.79	0.11	14.29	17.95	0.51	2.84	1414	387.62	27.40
		0.39		0.28	0.01	0.68	0.04	6.41	18.42	0.34	1.87	1561	282.10	18.07
		0.42		0.26	0.04	0.41	0.12	29.27	18.29	0.60	3.26	1584	52.10	3.29
	4.25	0.36		0.27	0.02	1.00	0.09	9.32	18.57	0.12	0.64	1334	225.33	16.89
		0.39		0.27	0.04	0.40	0.14	34.96	18.31	0.31	1.69	1330	112.62	8.47
		0.42		0.16	0.09	0.18	0.03	14.70	19.60	1.11	5.65	2026	489.06	24.14
	4.50	0.36		0.40	0.14	1.08	0.59	54.97	17.06	1.61	9.45	760	549.91	72.35
		0.39		0.27	0.02	0.54	0.10	17.67	18.77	0.37	1.94	1374	294.99	21.47
		0.42		0.27	0.01	0.40	0.07	17.94	18.61	0.16	0.86	1515	365.03	24.09

(1) Standard deviation
(2) Permeability
(3) Unit Weight
(4) Indirect Tensile Strength
(5) Coefficient of variation

Indirect Tensile Strength

Figure 7 represents the variation of ITS with respect to void ratio. ITS values ranged from 2026 kPa to 760 kPa as void ratios ranged from 0.16 to 0.46. The graph shows that ITS decreased when void ratio increased. Figure 8 represents the variation of ITS with w/c. The value of ITS for the mix with no CKD was achievable for other mixes where a percentage of cement was replaced by CKD. This indicated that adding CKD to the mix not only promoted sustainable development but also allowed the mix to maintain its mechanical properties. Findings from this study showed that the effect of w/c and A/C on the properties of pervious concrete were consistent with the behavior reported by previous studies (e.g., Chopra, et al., 2006).

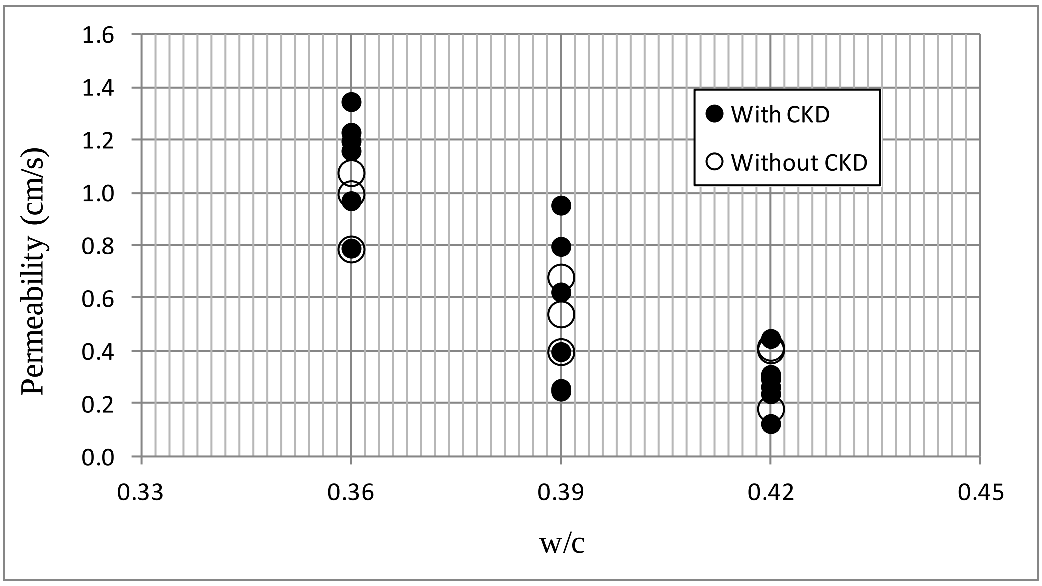

Figure 6 - Permeability vs. w/c Plot

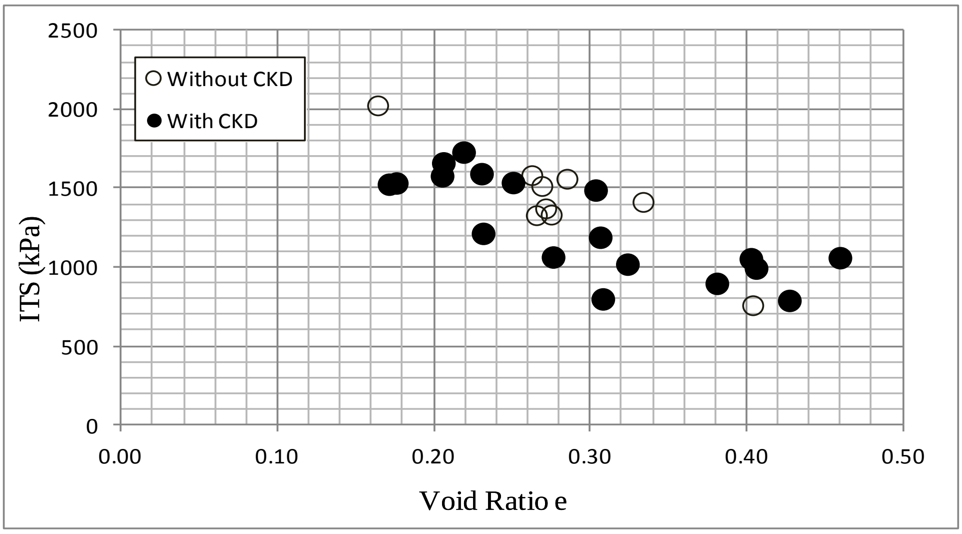

Figure 7 - ITS Variation with Respect to Void Ratio

Optimum Mix Design

Permeability is an important parameter of pervious concrete since the material is designed to perform as a drainage layer in pavement structures. Tensile strength must also be taken into consideration when using pervious concrete. An acceptable pervious concrete mix must, therefore, have adequate drainage and strength properties. ITS versus void ratio (e) and permeability (*k*) versus (e) were plotted on the same graph to compare results as shown in Figure 9. The optimum pervious concrete mix was determined by finding the intersection of the two curves. The intersection showed optimal mix was as follows: ITS of 1140 kPa, permeability of 0.73 cm/s and a void ratio of 0.328.

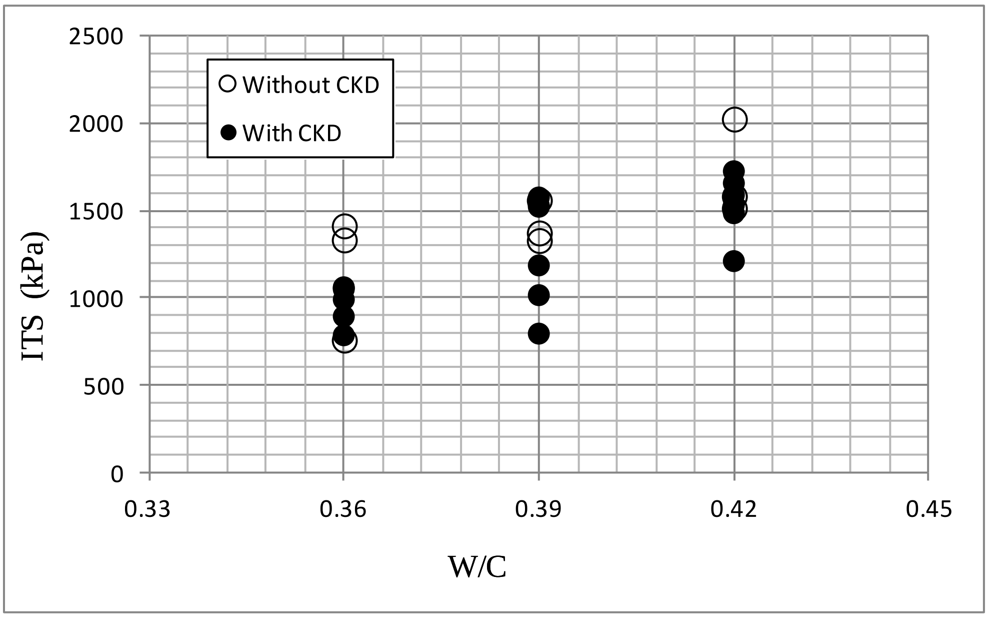

Figure 8 - ITS vs. w/c Plot

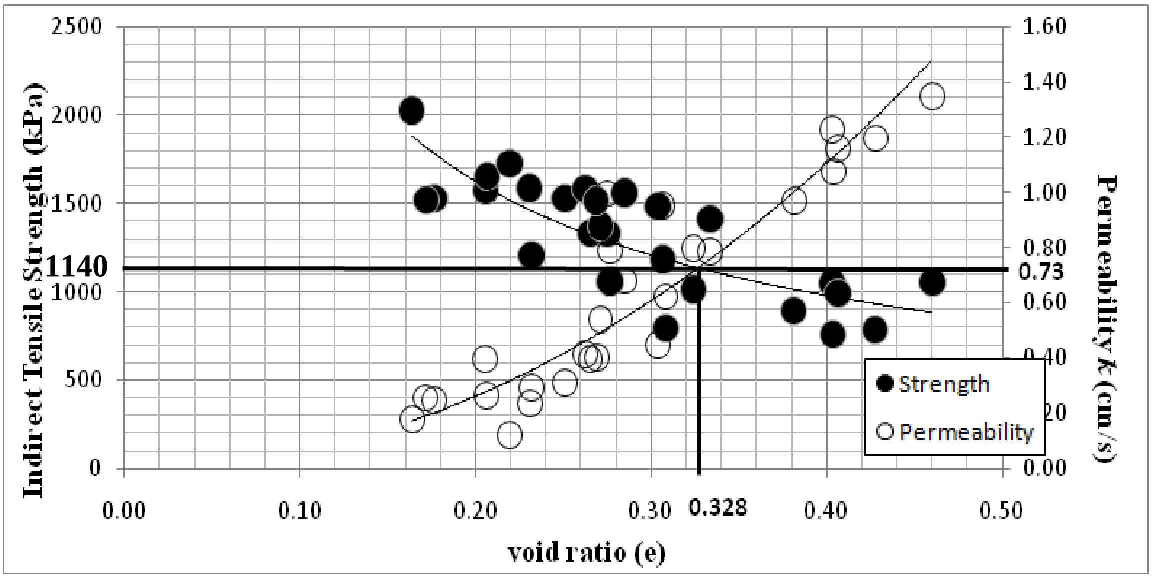

Figure 9 - Optimal Mix Properties

Conclusions

This study assessed the hydraulic and mechanical properties of CKD-modified pervious concrete mixtures. Specimens were prepared and tested for porosity, permeability, and (ITS). The mix design variables investigated in this study included: aggregate to cement ratio (A/C), water to cement (w/c), aggregate gradation and CKD percent replacement. Results showed a direct relationship between permeability and void ratio and an inverse relationship between permeability and water to cement ratio. There was an inverse relationship between ITS and void ratio and a direct relationship between ITS and the water to cement ratio. The optimal mix design had the following properties: ITS= 1140 kPa, w/c= 0.73 cm/s and void ratio= 0.328.

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