Hydraulic Conductivity Prediction of Cement Stabilized Pavement Base Incorporating Recycled Plastics and Recycled Aggregates

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***Abstract*—**Saturated hydraulic conductivity is one of the most significant attributes of pavement base course. Determination of hydraulic conductivity is a routine procedure for regular aggregate base courses. However, in many cases, a cement-stabilized base course is used with compromised drainage ability. Traditional hydraulic conductivity testing procedure is a readily available option which leads to two consequential drawbacks, i.e., the time required for the specimen to be saturated and extruding the sample after completion of the laboratory test. To overcome these complications, this study aims at formulating an empirical approach to predicting hydraulic conductivity based on Unconfined Compressive Strength test results. To do so, this study comprises two separate experiments (Constant Head Permeability test and Unconfined Compressive Strength test) conducted concurrently on a specimen having the same physical credentials. Data obtained from the two experiments were then used to devise a correlation between hydraulic conductivity and unconfined compressive strength. This correlation in the form of a polynomial equation helps to predict the hydraulic conductivity of cement-treated pavement base course, bypassing the cumbrous process of traditional permeability and less commonly used horizontal permeability tests. The correlation was further corroborated by a different set of data, and it has been found that the derived polynomial equation is deemed to be a viable tool to predict hydraulic conductivity.

***Keywords*—**Hydraulic conductivity, unconfined compressive strength, recycled plastics, recycled concrete aggregates.

I. Introduction

A considerable number of highway agencies, private entities, and independent researchers have completed or are in course of conducting a wide range of studies and investigative projects regarding the feasibility, environmental compatibility, and performance of using recycled products in pavement construction. Recycled alternatives for virgin aggregate in road construction applications are becoming more prevalent, particularly as granular and stabilized base course [1]. Recycled Crushed Concrete Aggregate (RCCA) is one of the most used recycled materials which is mostly prevalent as unbound base course. Approximately 2.6 million tons of RCCA are generated in the US every year [2]. Instead of landfill disposal, these recycled concrete aggregates can be used as an alternative to naturally available materials in pavement construction [3]. Pavement base applications are the most common uses for RCCA produced from concrete pavement slabs [4]. A well-designed base course system is constructed with a well-graded, durable material and is freely draining [5]. Many studies have evaluated the use of RCCA as pavement base course, and in general, RCCA is recognized as a mechanically sufficient base course substitute for virgin aggregate [1]. However, along with those conventional recycled materials, researchers have always been looking for unconventional materials to be used for pavement construction with a view to exploring additional options as substitutes to depleting natural virgin aggregates. Unconventional material understandably does not possess the required attributes according to the established specifications. This reflects the fact that a significant amount of research has been devoted to carrying out feasibility studies on using this substitute material with an eye toward sustainability from both an environmental and an economic perspective [6]. Recycled plastic could be one of those unconventional alternatives to virgin aggregates which hold great potential to be considered as a viable pavement construction material.

Incorporation of recycled plastics could be beneficial in two different ways, i.e., it could pave a convenient way to repurpose waste plastics, and at the same time it could lessen the excessive dependency on virgin aggregates for pavement construction. Prior to 1980, there was almost no recycling or burning of plastic; all of it was dumped. Rates climbed on average by around 0.7% year from 1980 for incineration and 1990 for recycling [7]. Around 55% of plastic garbage worldwide was thrown in 2015, while 25% was burned, and 20% was recycled [7]. In 2018, the total amount of waste plastics generated in the United States was 35.7 million tons, which counts for 12.2% of total Municipal Solid Waste (MSW) generation [8]. According to United States Environmental Protection Agency (USEPA), in 2018, landfills received 27 million tons of plastic which counts for 18.5% of total MSW being landfilled [8]. The holistic plastic pollution scenario in the USA has been lately exacerbated due to the much talked about Chinese ban on importing recycled plastics from the USA [7]. Initiation of a sustainable plastic waste recycling market in accordance with

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the principle of circular economy could help the USA to substantially reduce plastic pollution. Incorporation of recycled plastics in pavement construction is one of the most sustainable options which the USA could adopt to create a source of circular economy. Recycled plastics have long been considered as potential alternatives to act as a binder modifier for surface course. MacRebur, a business based in the United Kingdom, has devised a method for incorporating waste plastic into asphalt for road building and surfacing [9], [10]. When waste plastic is incorporated into the bituminous mix, it leads to a reduction in the amount of bitumen that is consumed, which in turn results in a reduction in expenses [11]. The utilization of discarded plastic in the construction of roads may also contribute to an increased road service life subject to advanced research and further studies. Although the incorporation of plastics into the construction of pavement is a relatively newer concept, it is easily discernible that the use of plastic in road construction across the globe is primarily limited to use in the surface/binder course as a substitute for bitumen [7]. However, the utilization of recycled plastics on a broader scale can be secured using appropriately shredded plastic particles as a substitute material for base course of a road [7].

Recycled materials (both conventional & unconventional) have been reported to be a very effective solution for reducing pavement maintenance and construction costs [12]. However, compared to virgin natural aggregates, recycled aggregates are weaker [13]. As a result, when recycled aggregates are utilized as an alternative for natural aggregates for pavement base construction, the minimum requirements of strength standards designated by AASHTO, and local state guidelines are not fulfilled [14]. Hence, to comply with the minimum strength requirements, different chemical and mechanical stabilization techniques are implemented [15]. One of the most common mechanical stabilization techniques is cement stabilization where one or numerous recycled materials are mixed with a certain percentage of cement. However, most of the previous research and studies mostly accentuate on determination of strength properties of stabilized road course. Number of studies conducted on hydraulic conductivity of cement stabilized recycled base course is sternly insignificant. In 2011, Hoyos et al. carried on a study of hydraulic conductivity of cement treated Recycled Asphalt Pavement (RAP) to be potentially considered for base course [16]. However, it is worth mentioning that very few studies till date have been conducted to quantify the hydraulic characteristics of a pavement base course made of recycled plastics, and recycled concrete aggregate stabilized by ordinary Portland cement. Subject to the cement stabilization, it takes a longer period for the samples to get saturated, and it is almost impossible to extrude the samples from the mold after the test in the conventional way. This study exclusively aims at envisaging an equation based on the correlation between experimental results of hydraulic and strength parameters of representative samples, which could predict the hydraulic conductivity of cement treated pavement base course made of recycled plastics and concrete aggregates.

II. Materials & Methods

Materials used for preparing the representative samples incorporate RCCA, multiple types (PET, HDPE) of shredded plastics, Ordinary Portland Cement (OPC), and water. Two different forms of recycled plastics (PET, HDPE) were mixed at three different constituencies (0%, 3%, and 5%). Cement stabilization was carried out in four different dosages (4%, 6%, 8%, and 10%). Samples with 0% plastic content would be treated as control samples regardless of plastic type. RCCA were collected from the site of Big City Crushed Concrete located in Dallas, Texas. Two types of plastic (PET, HDPE) were collected from Republic Services Material Recovery Facility, Fort Worth, Texas. To get rid of unwarranted impurities, collected plastics were cleaned by a diluted solution of sodium hypochlorite commercially known as liquid bleach. The mixture ratio of liquid bleach and clean water was maintained as 1:20. Plastics were drenched in the large container and left 2 hours for deep cleaning. Plastics are rinsed with clean water afterwards. Cleaned plastics were then air dried for 24 hours. Cleaned and dried plastics were transported to a shredding facility for primary shredding. Balcones Resources Inc. located in Dallas shredded the plastics into heterogeneous mesh size ranges from 0.5 inch to 3 inch. The secondary shredding was performed in the Civil Engineering laboratory building at the University of Texas, Arlington (UTA) using small scale shredder. For this study, INTBUYING 220V Heavy Duty Plastic shredder was used for secondary shredding purposes. For stabilization purpose, readily available OPC was used. To be precise, type I/II OPC was selected for stabilizing the samples.

After conducting the gradation analysis, and obtaining the Optimum Moisture Content (OMC), and Maximum Dry Density of the aggregates involved, sample mixing was carried out by a mechanical concrete mixer located at Geotechnical Engineering laboratory of UTA. Based on the calculated OMC, optimum amount of water was added to the mix according to the prescribed sample combinations with different cement dosages (4%, 6%, 8%, 10%).

Fig. 1 Material mixing

Having mixed the constituent ingredients, the mixed sample was ready to get filled in a compaction permeameter. For this experimental procedure, compaction permeameter (H-4145) manufactured by Humboldt was used. Having opened the upper cap of the compaction permeameter, mixed samples were placed in three different layers to fill the compaction permeameter, while each equally portioned layer was subject to 50 blows generated by an electro-mechanical proctor apparatus placed at the laboratory.

(a) (b)

Fig. 2 (a) Compaction permeameter; (b) Electro-mechanical compactor

After completing the compaction, the molded sample was ready to be cured in a moisture room for 7 days. After the curing period, the compaction permeameter was sealed carefully to assure that it did not come into the contact of free air, or any kind of fluid and the cured sample contained in the compaction permeameter was ready for the constant head permeability test. Upon completion of the sample saturation, the outlet of the compaction permeameter was kept open to collect the discharge in a scaled glass beaker. For 100 ml discharge, pertinent time was recorded using a stopwatch. The discharge was then converted to cubic cm and was reported in cm^3/sec. Because of the cement stabilization, time required for saturating the sample was observed substantially more than regular practice which led to an unavoidable procrastination to complete the test. After conducting the test in accordance with the standard ASTM D2434-19, hydraulic conductivity of the sample was calculated using the formula:

$$k = \frac{qL}{Ah} \tag{1}$$

where, k = hydraulic conductivity (coefficient of permeability) in cm/sec; q = discharge in cm^3/sec; L = length of the specimen in cm; A = cross sectional area of the specimen in cm^2; h = constant head causing the flow in cm.

Resulting hydraulic conductivities (cm/sec) then were converted to ft/day to follow the usual convention of hydraulic conductivity unit by using the following conversion: 1 cm/sec = 2834.65 ft/day.

On the other hand, Unconfined Compression Strength (UCS) tests were carried out following the specification of TxDOT under the guidelines of Tex-120-E. The specimens of 6 inches in diameter and 8 inches in height were prepared at the OMC. They were compacted in four lifts and each layer was subjected to 50 blows to achieve the required compaction. And then the samples were placed in a moisture room for curing for 7 days under a uniform temperature of 700 °F. After curing, the samples were placed on the platform of a Universal Testing Machine (UTM) and load was applied at a constant rate. To maintain a constant deformation rate on the specimen, the strain rate of 2:0 (within a range of 0:3%) was applied. Afterwards, Unconfined Compressive Strength (UCS) values were obtained from the incorporated computer program attached to the UTM.

Fig. 3 UCS test [6]

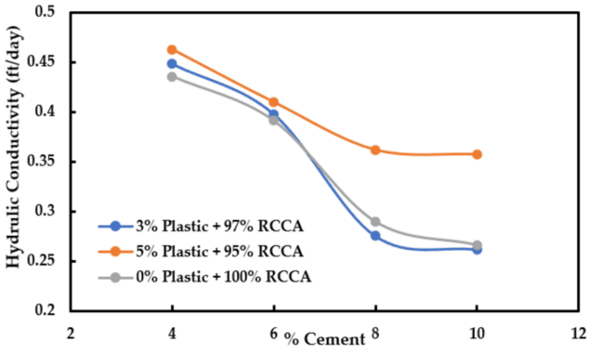
III. Results & Analysis

Representative samples are denoted as A (X-Y-Z), where A = Plastic type i.e., HDPE, PET; X = % plastic, Y = % Recycled Crashed Concrete Aggregate (RCCA), Z = % Cement. For example, PET (3-97-4) means the sample is made of 3% PET plastics, 97% RCCA stabilized by 4% cement. Similarly, HDPE (5-95-10) represents sample which is fabricated of 5% HDPE plastics, 95% RCCA and 10% cement stabilization. On the other hand, Control (0-100-8) means the sample is made of 100% RCCA stabilized by 8% Cement with 0% plastic. Results of these experimental tests consist of Hydraulic Conductivity and UCS test results. Both tests were conducted concurrently to maintain congruity of the experiments. While conducting both tests, it was ensured that the sample combinations remained the same possessing identical constituent parameters. After completion of both tests, the corresponding data were collected and tabulated.

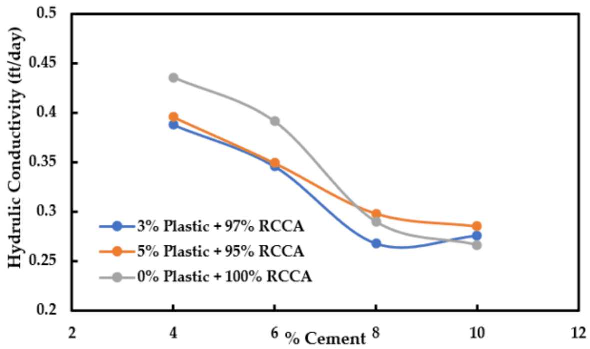
TABLE I
Summary of Test Results

Type of Plastic	% Plastic + % RCCA	% Cement	Hydraulic conductivity (ft/day)	UCS (psi)
PET	3% + 97%	4	0.45	250
		6	0.39	380
		8	0.28	480
		10	0.26	580
	5% + 95%	4	0.46	220
		6	0.41	250
		8	0.36	370
		10	0.36	385
HDPE	3% + 97%	4	0.39	290
		6	0.35	435
		8	0.27	585
		10	0.28	640
	5% + 95%	4	0.39	255
		6	0.35	400
		8	0.30	525
		10	0.29	625
Control	0% + 100%	4	0.44	300
	0% + 100%	6	0.39	380
	0% + 100%	8	0.29	450
	0% + 100%	10	0.27	630

It is imminent that irrespective of sample combinations, hydraulic conductivity tends to decrease conspicuously with increasing dosage of cement. In contrast, from Table I, it is eminent that increasing cement stabilization does ameliorate the mechanical strength of the representative samples. Graphs plotted based on the experimental results also corroborate this statement as exhibited in Figs. 4 and 5.



(a)



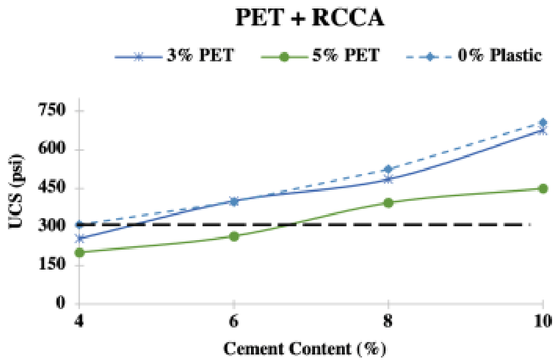
(b)

Fig. 4 Variation of hydraulic conductivity with respect to different cement dosages for samples incorporating: (a) PET plastics; (b) HDPE plastics

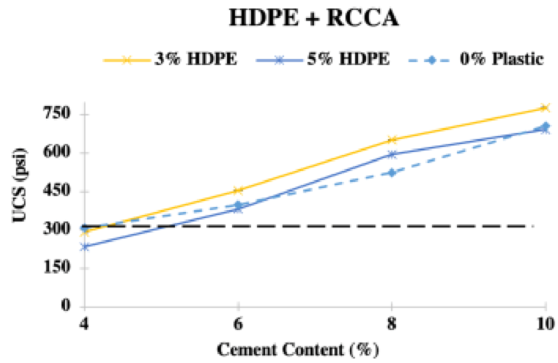
From Table I and Figs. 4 and 5, it can be observed that hydraulic conductivity and UCS of cement treated pavement base course incorporating recycled plastics and recycled concrete aggregates possess inverse relationship with respect to the degree of cement stabilization. This antithetical relationship could be an ideal platform to construct a polynomial equation which could be used to predict the hydraulic conductivity of cement treated samples without carrying out the cumbersome permeability test. Fig. 6 represents the correlation between resulting compressive strength and hydraulic conductivity of representative samples.

Fig. 6 suggests that there is a substantial correlation between the plotted experimental values of hydraulic conductivity and UCS with an impressive coefficient of determination (R2) value of 0.881. However, this correlation must be validated by a different set of data. For that purpose, different sets of representative samples were prepared incorporating a different type of plastic, i.e., PP. Table II summarizes the results of those aberrant sets of samples incorporating PP type of plastic.

To validate the credibility of the derived polynomial equation, we have to plot the actual experimental results against the predicted results using that polynomial equation as shown in Fig. 7.



(a)



(b)

Fig. 5 Variation of hydraulic conductivity with respect to different cement dosages for samples incorporating: (a) PET plastics; (b) HDPE plastics [6]

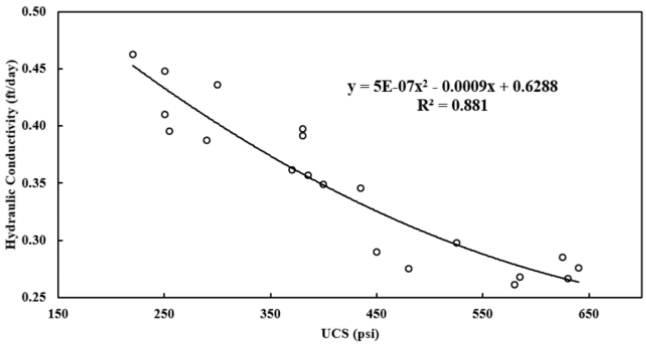


Fig. 6 Correlation between hydraulic conductivity and UCS

According to Fig. 7, derived polynomial equation can predict 92.45% of the variation in hydraulic conductivity in terms of corresponding UCS values implying a strongly credible prediction model.

IV. Conclusion

This study has been able to establish an exclusive correlation between two parameters of cement treated pavement base course made of recycled plastics and concrete aggregates. A polynomial equation ($y = 5E\text{-}07x^2 – 0.0009x + 0.6288$; where y is the hydraulic conductivity and x is the UCS) has been derived and validated to predict the hydraulic properties skipping the seemingly strenuous permeability test of cement treated base course. The correlation and the subsequent prediction equation have been validated by an independent set of data which solidifies the validity of this simple polynomial model. However, this study has got some limitations as well. Importantly, this prediction does not consider the consequences of plastic percentage and recycled concrete aggregates present in the samples on relative change of their hydraulic characteristics and the compressive strengths. A more detailed regression model incorporating those two constituent parameters alongside cement dosages could be considered for future studies.

TABLE II
TEST RESULTS FOR PP SAMPLES

Type of Plastic	% Plastic + % RCCA	% Cement	Actual Hydraulic Conductivity (ft/day)	UCS (psi)	Predicted Hydraulic Conductivity (using equation) (ft/day)
PP	3% + 97%	4	0.45	250	0.44
		6	0.39	380	0.36
		8	0.28	480	0.31
		10	0.26	580	0.28
	5% + 95%	4	0.46	220	0.46
		6	0.41	250	0.44
		8	0.36	370	0.36
		10	0.36	385	0.36

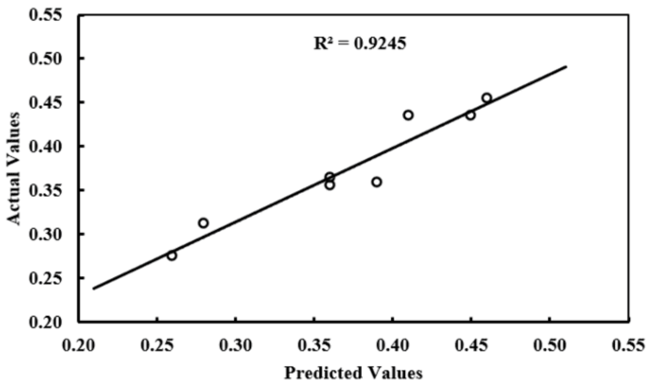


Fig. 7 Validation of prediction equation

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