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Polyethylene terephthalate usage as a partial replacement for recycled fine aggregate in the subbase layer

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Abstract. The best way to dispose of construction waste and plastic materials (in Mosul city in the north of Iraq) is to use them as subbase layer of the road to make them both environmentally friendly and cost-effective. Because these materials are not cohesive, a certain percentage of clay was added. The research aimed to dispose of these materials scientifically and deliberately with appropriate California Bearing Ratio (CBR) values obtained from a mixture of (clay soil + recycled concrete aggregates (RCA) + polyethylene). These values are much greater than the CBR values obtained from natural materials used in the design of the road subbase layer. Clay was added to soil in specific proportions: 10 % to type A and 20 % to type B. Various tests were carried out for the mixture to determine Maximum Dry Density (MDD) and Optimal Moisture Content (OMC), and then CBR and swelling. Tests were also carried out to determine the soil permeability (both the permeability rate in centimeters per hour (cm/h), and the coefficient of permeability k in meters per second (m/s)). Polyethylene was added in different proportions as a replacement for the remaining fine aggregate on the sieve No. 8. Multiple percentages of polyethylene terephthalate were used, ranging from 2.5 to 10 for type A (2.5, 5.0, 7.5, 10 %) and from 5 to 20 for type B (5.0, 10, 15, 20 %), in order to obtain an ideal mixture of (RCA + polyethylene + clay). The CBR was 12 %, which had been more than that of natural soil. The coefficient of permeability was more than 32 m/day, indicating that these mixes could be used for subsurface drainage purposes. This value was reasonable and no noticeable erosion was observed. The subbase would help draining and prevent settlement and channeling. Apart from the sustainable benefit, the mixture (clay soil + RCA + polyethylene) was found to be suitable for use in road pavements, according to the methodologies used in this study. Due to the encouraging results it is recommended to use these techniques to dispose of the waste and debris materials and obtain optima benefits.

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1. *Introduction*

Despite Iraq's natural aggregate reserves, this study focuses on recycled concrete as a major road material to dispose of trash productively and safely. Crushed waste materials from demolished buildings generate a variety of particle sizes that meet the gradations criteria of Iraqi subbase course standards. Because concrete cement mix is one of the most commonly used building materials in Iraq, the demolition of existing structures under the country's current conditions has resulted in a large amount of concrete waste that must be used as useful materials to achieve environmental, economic, and social benefits.

There are three main types of construction and demolition waste aggregates: MRA (mixed recycled aggregates – also known as mixed demolition debris), RCA (recycled concrete aggregates), and RMA (recycled masonry aggregates – also known as Crushed Clay Masonry, RCM) [1, 2]. Some 60 % of the materials used in the construction of a building come with concrete (Fig. 1a), and 42 % of the wastes generated by the construction sector are concrete wastes (Fig. 1b) [3, 4].

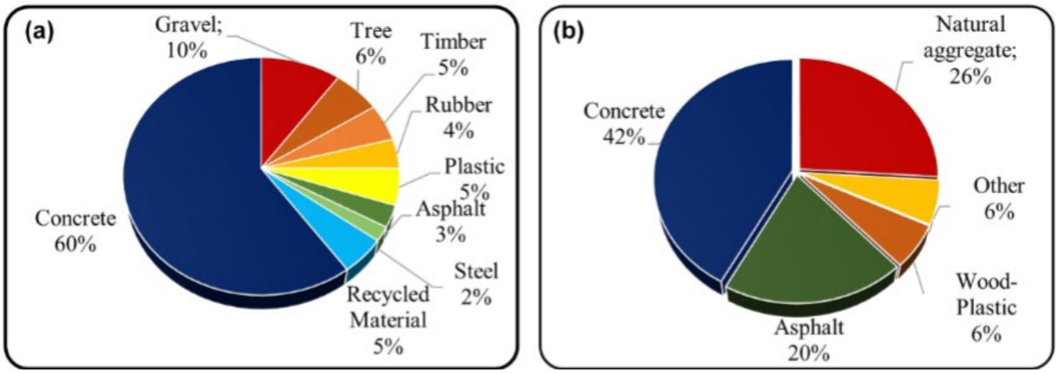


Figure 1. The proportion of materials used for the construction of a building (a) and waste rates (b) [7].

Within the specified restrictions, the researchers discovered that recycled aggregate may be used in road layers (base or subbase) [5].

The most prevalent application of RCA is in pavement (subbase, base) materials, although it has also been used in concrete and asphalt paving layers, as well as general fill and embankment material, and in a variety of other uses. We summarized the usage of RCA in paving applications in Fig. 2 [6].

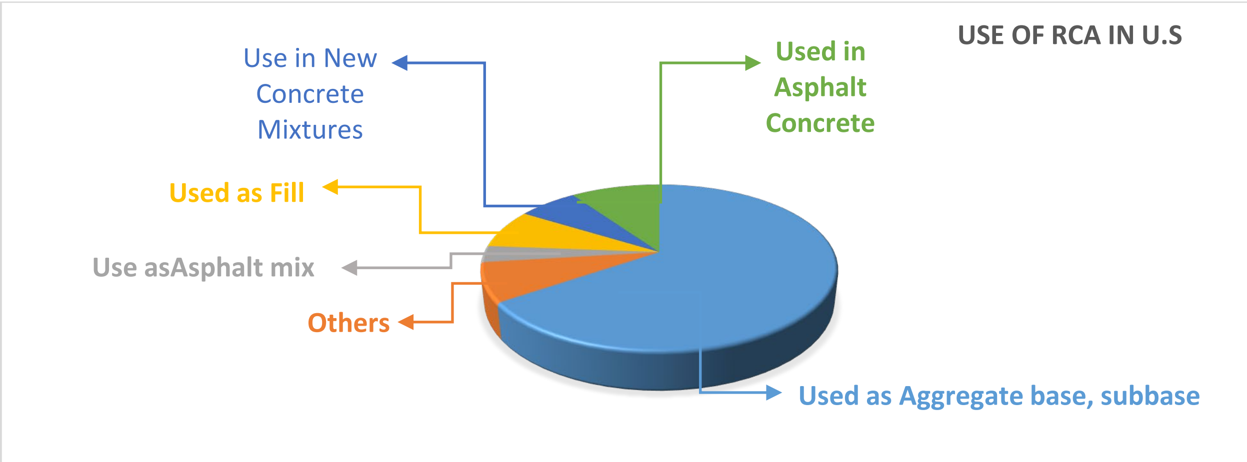


Figure. 2. An overview of RCA's utilization in paving applications.

Increasing RCA content in the mixture causes an increase in Optimum Moisture Content (OMC) and a decrease in Maximum Dry Density (MDD). Fine aggregates formed during the compaction process have a negative effect on the performance of the foundation and subbase layers, especially on the hydraulic properties. The California bearing ratio (CBR) value of RCA is equal to or higher than typical natural aggregates (NA) in relation to use in road pavement foundation and subbase layers. In addition, RCA provides the minimum specification limit required for road applications even when it has a lower CBR value than NA. CBR values vary between 67 % and 190 %. CBR values are believed to vary in such a wide range because the properties of the source concrete samples used in the studies are different from each other [7]. Compared with the crushed aggregate, the CBR values of the mixtures containing RCA were found to be between 118 % and 160 %. It was reported to be suitable for use in the base and subbase layer of RCA, as it meets the minimum 80 % CBR value specified in the Australian local state highway specification [8]. The CBR test's results suggest that CBR values obtained from recycled concrete are significantly higher than those CBR values obtained from the ordinary subbase. As a result, it is possible to conclude that recycled concrete might be used as a subbase material for highways [9]. The preceding paragraphs emphasized the advantages of RCA as compacted aggregates or stabilized mixtures. However, the application of RCA in mixtures with clay soils to improve the bearing/shear strength of the subgrade has never been investigated [10]. Due to the wide use of plastics in human daily life, the rate of plastic waste generation is increasing at an alarming rate. Every year almost 2.24 million tons of plastic waste is produced in Australia [11].

The deformation behavior of construction and demolition waste materials, such as RCA and crushed brick (CB) that were mixed with up to 7 % polyethylene terephthalate (PET) plastic waste, was investigated in [12]. It was found that increasing the PET content and stress levels increased the permanent strain of blends. It is recommended that up to 3 % PET could be mixed with RCA in base/subbase layer. [13–15] used plastic wastes for the sustainable construction of flexible pavements. In [12] it stated clearly that "the addition of plastic waste to pavement granular materials can considerably influence the strength and deformation properties of materials, which need to be fully understood prior to their wide usage for construction of pavement base/subbase layers".

The outcome of [16] illustrated that the modified subbase properties were significantly enhanced by adding the waste plastic granules and that, for best results, the optimal percentage of recycled PET granules to be added was 10 % by the volume of the subbase material. The CBR value for modified subbase, as compared with the subbase without waste plastic, increased by as much as 36 %. It has been suggested that this method could provide a potential practical use for waste plastic as well as improve the quality of subbase soil layers for flexible pavement.

The experimental results in [17] indicated that the insertion of plastic waste increased the OMC and reduced the MDD and CBR. Modified subbase layer also met the requirements of applicable standards codes. Based on these outcomes, it was suggested, that the use of plastic waste in subbase layers had been feasible for practical work [16].

Using plastic waste for soil stabilization can help to enhance pavement foundation layers [18].

Results of CBR tests in [19] revealed that inclusion of waste high density polyethylene strips in soil in suitable proportions significantly improved strength and deformation behavior of subgrade soils. The proposed technique could be beneficial in embankment/road construction.

Five types of subbases ranging from an impermeable cement stabilized material to a very permeable, uniformly graded, crushed aggregate were evaluated during a 7-year research project [20], which demonstrated that "open-graded, permeable, subbase materials could be designed to provide adequate constructability and pavement support as well as good internal drainage at a competitive cost".

Moisture enters into the pavement structure from the surface by infiltrating through cracks and joints, laterally from shoulders, and as capillary suction from bottom. One of the main reasons for the accumulation of moisture is inadequate subbase permeability. The presence of moisture within the pavement structure reduces the structural stability of the system. Therefore, it is essential to provide the subbase layer with sufficient drainage characteristics. In [21] horizontal permeability was determined using laboratory-developed horizontal permeameter under constant head mode with different hydraulic gradients. Strength characterization was also done in terms of CBR value.

The coefficient of permeability, k, a unit of velocity, is a measure of the ease with which fluids can travel through a porous medium. In [22] multiple regression equation was developed by comparing maximum hydraulic conductivity with parameter affecting K values such as Voids ratio e, 75micron passing material and effective grain size material D_{10}.

Darcy's law is generally expressed as:

$$v = k * i,$$

where v is flow discharge velocity in cm/s; k is coefficient of permeability in cm/s; i is hydraulic gradient.

Using the specific sign convention, Darcy's law is expressed as:

$$Q = -KA\ dh/dl$$

where Q is rate of water flow; K is hydraulic conductivity; A is column cross section area; dh/dl indicates hydraulic gradient [28].

As per compaction test conducted and obtained MDD of 2.14 gm/cc and OMC of 3.18 % to be achieved in the field. Permeability test conducted in the field for Grade III at 2.5 %, 3.5 % and 4.0 % hydraulic gradients. At 2.5 % hydraulic gradient maximum hydraulic conductivity of 3675.66 m/day was observed [22].

During wet seasons, when the subgrade becomes saturated, cyclic loading, caused by heavy traffic, may result in the pumping of fine particles from the subgrade into the granular layers, which may lead to pumping in a concrete road. It is expected that the erosion may be less due to the presence of polyethylene. The resulting gradation from the migration of subgrade fines into the subbase also varies with the depth in the subbase with more fines deposited in the lower section (closer to the subgrade) than in the upper section of the subbase [23].

For example, if a k of 5.000 ft/day is needed, one should be able to see openings between particles at least 1/20 inch in diameter; if 20.000 ft/day is required, visible openings should be at least 1/10 inch in diameter; and for 100.000 ft/day, at least 1/4 inch. The making of even such a crude "eye test" can help designers avoid serious mistakes in selecting types of aggregates to be use in drainage systems.

A permeable material is one that is capable of being penetrated or permeated by another substance, usually gas or liquid. Thus, dry cement is permeable to air, and an air permeability test is a useful means of obtaining an indirect measure of its fineness of grind, since the speed of flow of air through it can be related to the size of the pore spaces between the particles. Likewise, soils and aggregates and jointed, cracked, or vesicular rocks are often permeable to air and water [25].

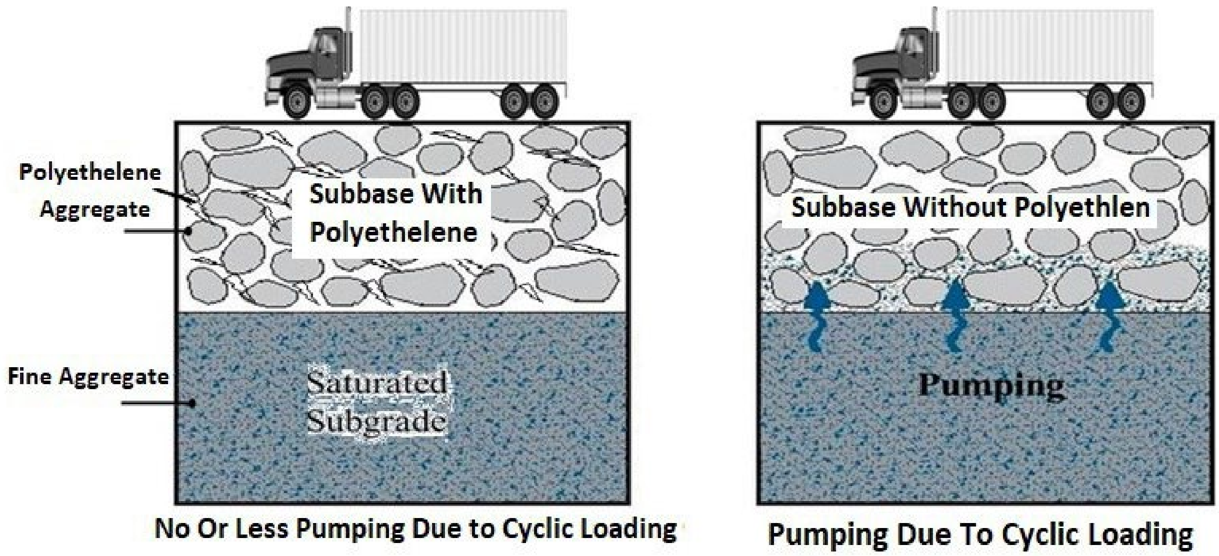


Figure. 3. Relationships between pumping through the layers with and without polyethylene.

Table 1. Some typical values of hydraulic conductivity [24].

Unconsolidated deposits	Hydraulic conductivity, m/s	Rocks	Hydraulic conductivity, m/s
Dense clay	10^{-13} ……10^{-8}	Dense sandstone	10^{-9} ……10^{-7}
Weathered clay	10^{-8} ……10^{-6}	Karstic sandstone	10^{-7} ……10^{-5}
Silt	10^{-7} ……10^{-5}	Dense limestone	10^{-9} ……10^{-7}
Alluvial deposits	10^{-5} ……10^{-3}	Karstic limestone	10^{-5} ……10^{-3}
Fine sand	10^{-5} ……10^{-4}	Dolomite	10^{-10} ……10^{-8}
Medium sand	5×10^{-4} ……5×10^{-3}	Dense crystalline rocks	10^{-13} ……10^{-12}
Coarse sand	10^{-4} ……10^{-3}	Fractured crystalline	10^{-10} ……10^{-6}
Fine gravel	10^{-3} ……5×10^{-1}	Dense basalt	10^{-13} ……10^{-10}
Medium gravel	5×10^{-2} ……10^{-1}	Fractured basalt	10^{-7} ……10^{-4}
Coarse gravel	10^{-2} ……5×10^{-1}	Claystone	10^{-13} ……10^{-9}

This research aims to dispose these debris materials scientifically and deliberately with appropriate CBR values obtained from a mixture of (clay soil + RCA + polyethylene). The study conducted various tests and reached conclusions regarding the feasibility of this study.

2. *Materials and Methods*

2.1. *Recycled Concrete Aggregate*

The recycled aggregate was obtained from the debris of destroyed houses in Mosul. The UN estimates, that there are more than ten million tons of rubble in the city of Mosul. The military actions that took place in the capital of Nineveh Governorate after the ISIS occupation of the city resulted in this significant amount of debris, since a third of the city was completely destroyed, and a half suffered significant damage. This research was conducted to determine the suitability of these debris for road construction. The results of RCA and natural aggregate testing are shown in the Table 2.

Table 2. Results of RCA and natural aggregate testing.

Data	Value	Specification
Constant head permeability	$1.726*10^{-4}$	ASTM D2434-19
Plastic limit	NON	ASTM D4318-17e1
Liquid limit	NON	ASTM D4218-20
Shrinkage limit	NON	ASTM D4943-18
Specific gravity of fin aggregate (RCA)	2.57	ASTM C127-15, C128-15
Specific gravity of coarse aggregate (RCA)	2.45	ASTM C127-15, C128-15
Absorption of fine aggregate (RCA)	6.40 %	ASTM C127-15
Absorption of coarse aggregate (RCA)	1.70 %	ASTM C128-15
Specific gravity of natural fine aggregates	2.62	ASTM C127-15, C128-15
Specific gravity of natural coarse aggregates	2.67	ASTM C127-15, C128-15
Absorption of natural fine aggregates	2.07 %	ASTM C127-15
Absorption of natural coarse aggregates	0.73 %	ASTM C128-15
Soundness of fine aggregate (RCA) in sodium sulphate	2.7 %	ASTM C88/C88M-18
Soundness of coarse aggregate (RCA) in sodium sulphate	0.85 %	ASTM C88/C88M-18
Soundness of fine aggregate (RCA) in magnesium sulphate	2.6 %	ASTM C88/C88M-18
Soundness of coarse aggregate(RCA) in magnesium sulphate	0.6 %	ASTM C88/C88M-18
Soundness of natural fine aggregates in sodium sulphate	3.3 %	ASTM C88/C88M-18
Soundness of natural coarse aggregates in sodium sulphate	0.8 %	ASTM C88/C88M-18
Soundness of natural fine aggregates in magnesium sulphate	2.67 %	ASTM C88/C88M-18
Soundness of natural coarse aggregates in magnesium sulphate	0.65 %	ASTM C88/C88M-18
Los Angeles test (RCA)	29.6 %	ASTM C131/C131M–20

2.2. Clay

The clay samples were taken from the archeological region near the wall surrounding the ancient city of Nineveh at a depth of 1 m. According to the AASHTO Soil Classification System, the clay was pale reddish-brown, and was classified as A-2-6. According to the Unified Soil Classification System (USCS), the soil is (OH) organic clays of medium to high plasticity. The following tests were carried out:

1. Sieving of the particles through the No. 200 sieve according to ASTM D422-63(2007) to test the distribution of particle sizes in soils.
2. Calculation of specific gravity of soil solids according to ASTM D854.
3. Analysis of total soluble salts.

4. Soil organic matter chemical analysis in accordance with BS EN 1744-1:1998 and BS EN 1744-1:2009.
5. Analysis of the amount of gypsum in clay.
6. Atterberg limit test according to AASHTO T90 and ASTM D4218-20, ASTM D4318.
7. Determination of the shrinkage limit according to ASTM D4943.

2.3. Polyethylene Terephthalate

This study used recycled materials and waste to create a low-cost and environmentally friendly subbase. The waste plastic was used. Polyethylene was used as an additive to RCA at a percentage of clay soil (fine materials passing through the No. 200 sieve). It was used in following proportions: 2.5 %, 5 %, 7.5 %, and 10 % with type A and 5 %, 10 %, 15 %, and 20 % with type B – to increase the strength of the subbase layer. The polyethylene used is shown in Figure 4. It was mixed with graded recycled concrete aggregates of both A and B types.

Figure 4. The PET used in this study.

3. Results and Discussion

3.1. Clay Soil Test Results

The properties of the clay soil used with RCA as a binder for aggregates are presented in the Table 3.

Table 3. The results of the clay soil tests.

Data	L.L	P.L	P.I	SH.L	Clay size	Specific gravity	Soil organic matter	Total soluble salts	Amount of gypsum
Soil test results	38.6 %	23.9 %	14.7 %	5 %	56 %	2.577 %	7.8 %	1.2 %	10.5%

3.2. Recycle Concrete Aggregate

Gradation, or particle size distribution, for types A and B are shown in Fig. 5 and 6 respectively.

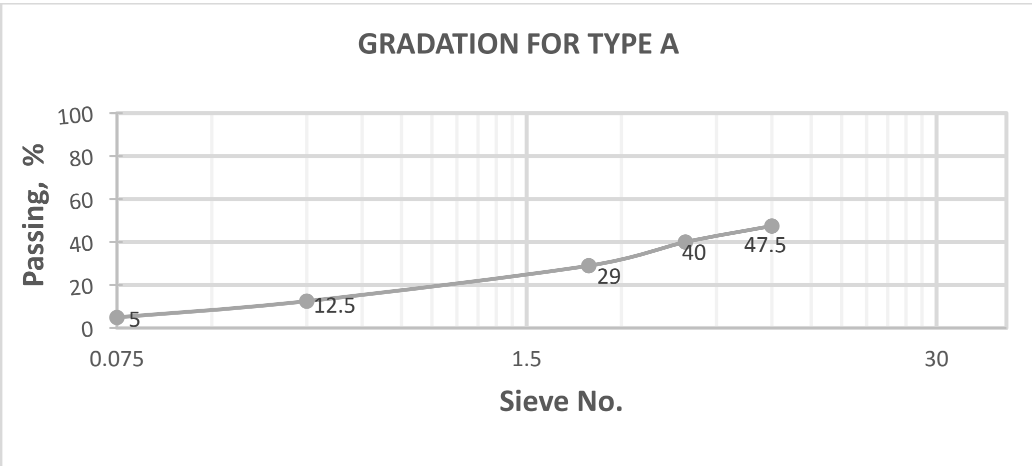


Figure. 5. Gradation for type A.

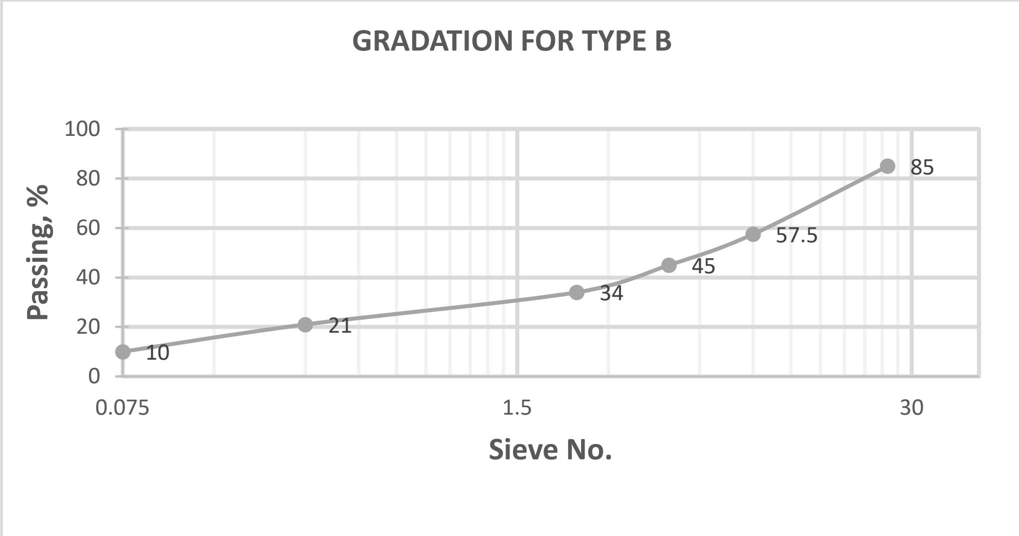


Figure. 6. Gradation for type B.

3.3. Polyethylene Terephthalate

Table 4 shows the results of the physical tests conducted on polyethylene. Fig. 7 shows the gradation for polyethylene.

Table 4. The results of the physical tests conducted on polyethylene.

Data	Specific gravity	Absorption, %	Degree of burning	Degree of softening
Polyethylene test result	1.54	0.5	275	125

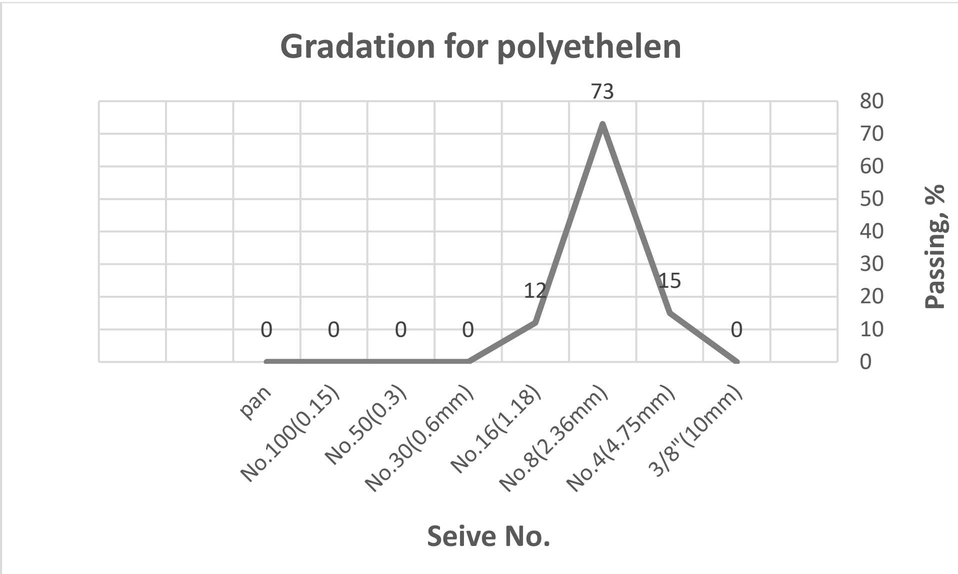


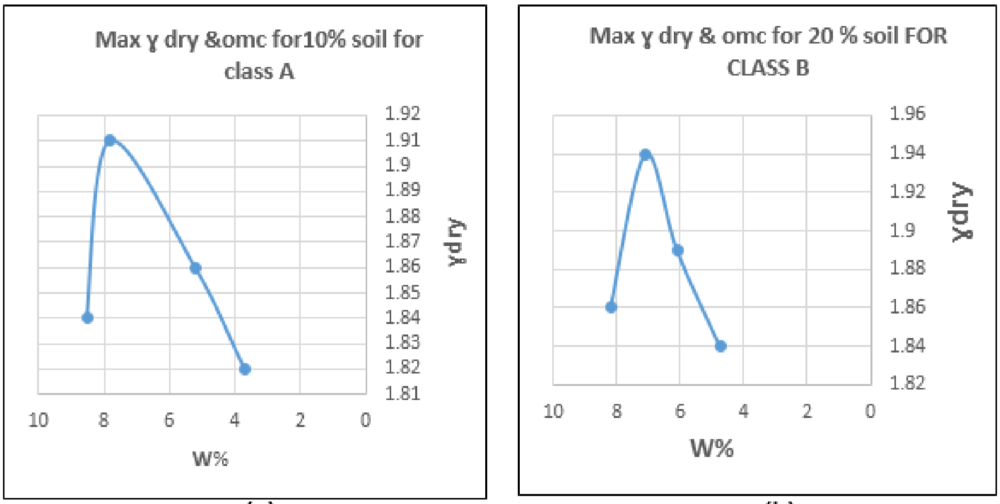
Figure. 7. Gradation for polyethylene.

3.4. Proctor compaction test

Proctor Compaction test was conducted according to ASTM D698/AASHTO T99 and ASTM D1557/AASHTO T180. Samples were crushed to pass through sieves 1”, 3/8”, No. 4, No. 8, No. 50, No. 200, and pan for MDD and OMC.

Table 5. The values of MDD and OMC.

Data	Percentage of clay in soil, %	MDD for (RCA + soil), gm/cm^3	OMC for (RCA + soil), %
Type A	10	1.91	7.8
Type B	20	1.94	7.1



(a) (b)

Figure. 8. (a, b) W % and omc relationships for class A (a) and B (b).

3.5. California Bearing Ratio (CBR) test

CBR test was conducted according to AASHTO T193 and ASTM D1883. Table 6 shows the results. And Fig. 9 and 10 show the added percentages of polyethylene and the results of CBR test values for types A and B.

Table 6. CBR test values.

Type A					Type B				
Percentage of polyethylene with (10 % Soil + RCA), %	OMC for (RCA + soil), %	Soaked CBR test, %	Unsoaked CBR test, %	Swelling, %	Percentage of polyethylene with (20 % Soil + RCA), %	OMC for (RCA + soil), %	Soaked CBR test, %	Unsoaked CBR test, %	Swelling, %
2.5		105.7	118.3	0.12	5		121	131.4	0.19
5		78	81.2	0.22	10		75	78.2	0.27
7.5	7.6	56.6	60	0.32	15	7.0	52.1	58	0.42
10		41	44.3	0.57	20		40.4	47.1	0.55

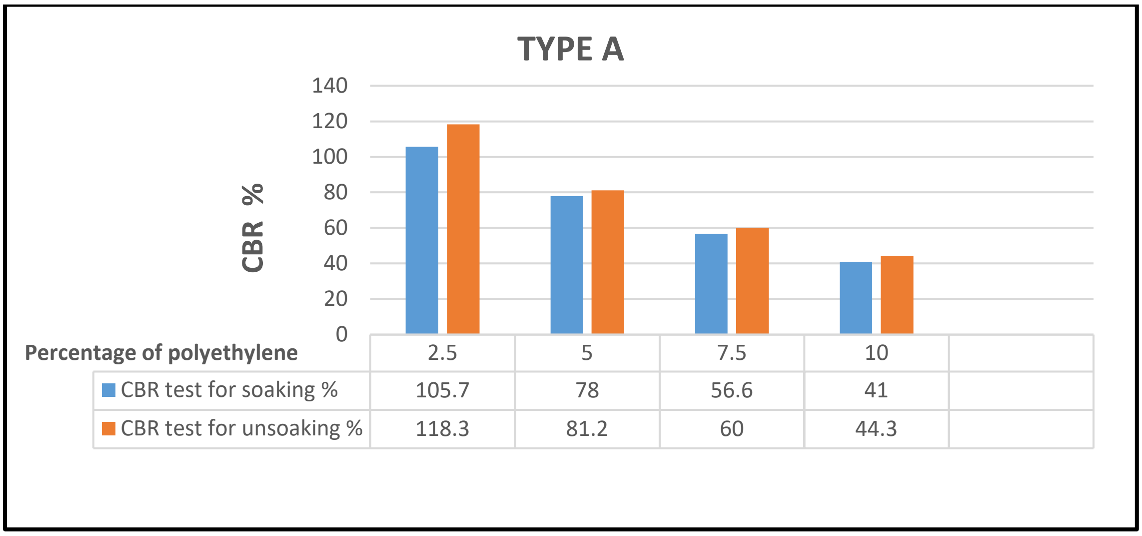


Figure. 9. Relationship between percentage of polyethylene and CBR test value for type A.

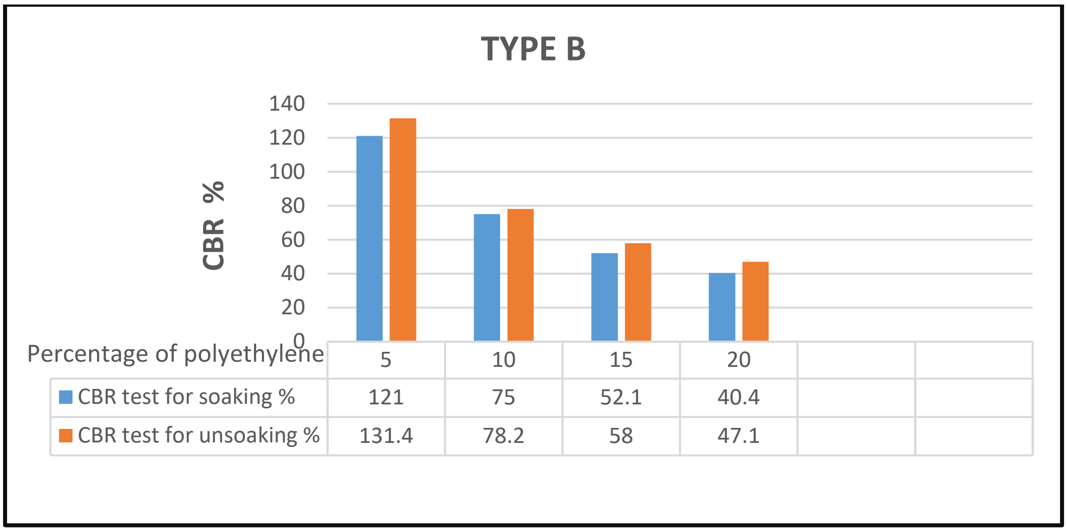


Figure. 10. Relationship between percentage of polyethylene and CBR test value for type B.

Figure. 11. CBR testing.

3.6. Permeability

Permeability is the ability of water to flow through soil/sediment/rock. It is controlled by:

a) porosity;

b) grain size;

c) interconnection of the pores;

- sand/gravel: high permeability – high porosity, good interconnection of pores (k = 0.1 – 1000's m/day);
- clay: very low permeability – high porosity, moderate interconnection of the pores, very small pore size (k = <0.01 m/day) [27].

The coefficient of permeability for RCA mixes is more than 32 m/day, indicating that these mixes can be used for subsurface drainage purposes. Such a layer can also serve as a structural layer which is a lower subbase, but without desired drainage properties.

3.7. Erosion

The permeability test result, as shown in Fig. 12, was 0.032 m/s, according to Darcy's law. It could be compared with the values in Table 1 for Medium sand (0.0005–0.005 m/s). This value is reasonable and no noticeable erosion was observed.

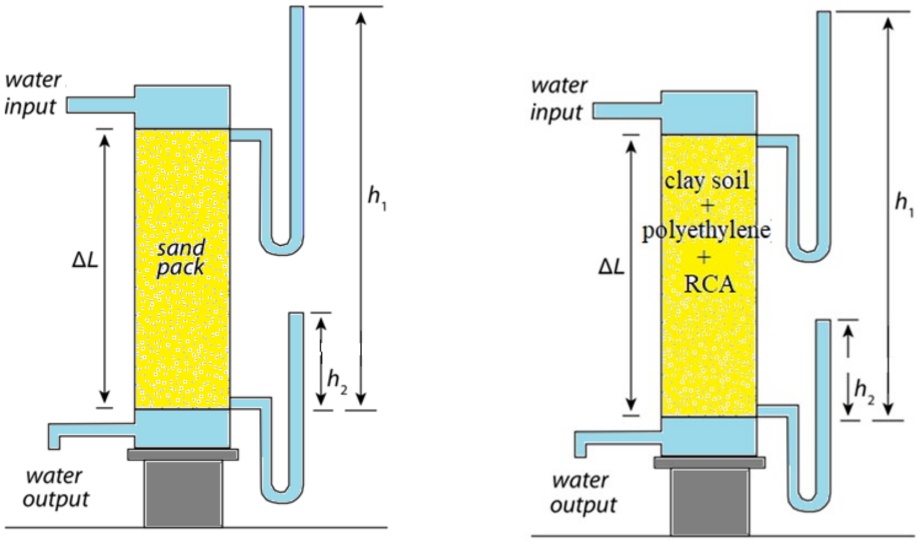


Figure. 12. Schematic of Darcy's original experimental apparatus (source: Maureen Feineman, Pennsylvania State University) and apparatus, used in experiment.

4. Conclusions

This study focused on the use of waste materials such as demolition rubble and polyethylene in the design of subbase layer of the road. The impact of these wastes on CBR performance was also examined. In light of the results obtained, we were able to come to the following conclusions:

1. All tests carried out on recycled concrete were in accordance with US and Iraqi specifications in terms of Specific gravity, Absorption, Durability, L.A. Abrasion test.
2. There were two types (A, B) of granular subbase.
3. Clay soils had liquid limit 38.6 %, plastic limit 23.9 %, plasticity index 14.7 %, shrinkage limit 5 %, specific gravity 2.57, soil organic matter 7.8 %, total soluble salts 1.2 %, and amount of gypsum 10.5 %. According to the AASHTO Soil Classification System, it is classified as A-2-6. According to the Unified Soil Classification System (USCS), it is organic silty clay with low plasticity.
4. Recycled aggregates were used after the sieving test, carried out according to SORB.
5. It was concluded that the higher the percentage of polyethylene materials added, the lower the CBR value for types A and B. When adding 2.5 % of polyethylene, the CBR value was 105.7 % for the soaked sample and 118.3 % for the unsoaked sample. When adding 10 % of the polyethylene, the CBR value was 41 % for the soaked sample and 44.3 % for the unsoaked sample for type A. When adding 5 % of polyethylene, the CBR value was 121 % for the soaked sample and 131.4 % for the unsoaked sample. But when adding 20 % of the polyethylene, the CBR value was 40.4 % for the soaked sample and 47.1 % for the unsoaked sample for type B.
6. During the CBR testing, it was found that the CBR value of unsoaked samples had been higher than the CBR value of the soaked samples. Because the polyethylene pieces, when added to the mixture (RCA + clay soil) filled the spaces between the aggregate particles and made the sample cohesive. When the sample was immersed in water for 96 hours, water entered the sample and swelled the clay soil in the mixture, causing the polyethylene pieces to slide out of place, leaving empty spaces. These voids weakened the strength of the sample.
7. The use of the mixture (RCA + clay soil + polyethylene) gave satisfactory results in the tests, and the CBR value of the waste mixture exceeded the value specified in SORB for the design of the subbase layer.
8. The mixture (RCA + clay soil + polyethylene) could be used in the design of the subbase layer for the environmentally friendly roads.

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