Ain Shams Engineering Journal (2013) **4**, 661–673

Ain Shams University

Ain Shams Engineering Journal

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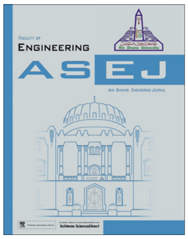

CIVIL ENGINEERING

Utilization of cement treated recycled concrete aggregates as base or subbase layer in Egypt

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Received 13 November 2012; revised 21 January 2013; accepted 14 February 2013
Available online 16 March 2013

KEYWORDS

Recycled concrete;
Cement treatment;
Tensile strength;
Compressive strength;
Resilient modulus;
Base aggregate

Abstract Recently, environmental protection has a great concern in Egypt where recycling of increased demolition debris has become a viable option to be incorporated into roads applications. An extensive laboratory program is conducted to study the feasibility of using recycled concrete aggregate (RCA) mixed with traditional limestone aggregate (LSA) which is currently being used in base or subbase applications in Egypt. Moreover, the influence of mixture variables on the mechanical properties of cement treated recycled aggregate (CTRA) is investigated. Models to predict the compressive and tensile strengths based on mixture parameters are established. The results show that the adding of RCA improves the mechanical properties of the mixture where the unconfined compressive strength (UCS) is taken as an important quality indicator. Variables influencing the UCS such as cement content, curing time, dry density play important roles to determine the performance of CTRA.

1. Introduction

Aggregate is an industrial commodity term for sand, gravel, and crushed rock materials, in their natural or processed state, that are used to provide bulk strength and resistance in construction applications. Demolition debris such as crushed concrete, crushed masonry mortar, and asphalt pavement has been significantly recycled since the end of the second world war. However, studies about its physical properties, mechanical behavior, and durability are quite recent. Reclaimed Portland cement concrete is the most abundant and available of the potential substitutes for natural aggregate in urban areas, especially in Egypt. Recycling of demolition debris into new construction offers a way to reduce waste disposal loads sent to area landfills and to extend the life of natural resources [1]. Many federal and state highway contracts specify use of recycled materials in highway construction where the rate of this usage is influenced by the availability, engineering performance, and by financial and other marketplace incentives that encourage the use crushed concrete as recycled aggregate. Recently, numerous laboratory studies and field trials have shown

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Abbreviations: CBR, California bearing ratio; CTRA, cement treated recycled aggregate; FS, flexural strength; ITS, indirect tensile strength; LSA, limestone aggregate; MDD, maximum dry density; Mr, resilient modulus; OMC, optimum moisture content; Pdr, plastic deformation ratio; PI, plastic index; RCA, recycled concrete aggregate; UCS, unconfined compressive strength.

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Peer review under responsibility of Ain Shams University.

ELSEVIER Production and hosting by Elsevier

http://dx.doi.org/10.1016/j.asej.2013.02.005

that recycled aggregate can totally or partially replace natural aggregates in road construction [2].

Potential saving in cost and time of recycling of construction and demolition debris has made the use of recycled concrete aggregate (RCA) an attractive alternative to the highway engineer. To utilize large volumes of construction and demolition debris, the minimum standards set by AASHTO, as well as the local specifications, must be met. Since these recycled materials may be generated on the job site, the quality control of these recycled materials may change during the course of the project. Therefore, highway engineers may choose to blend the recycled materials with quarried dense graded aggregate which currently being used in base or subbase applications [3]. Although many authors have studied the possibility of using RCA in applications, there are a few researches on the properties and mechanical behavior of mixtures treated with cement when used as road subbases or base in paving roads because of the following reasons [4]:

- improving the workability of road materials;
- increasing the strength of the mixture;
- enhancing the durability;
- increasing the load spreading capacity.

Cement treated aggregate is described as a mixture in which a relatively small amount of cement is used as a binder of coarse aggregates, and which needs a proper water content for both compaction and cement hydration. Generally, cement treated aggregate as a road base material is produced by using coarse natural or crushed aggregates and designed as a heavy traffic base or a heavy traffic wearing course. Recently, in order to protect the natural resource and reduce the environmental pollution of solid waste, recycling aggregate has been considered to be used in road bases [5].

2. Recycled concrete aggregate

When using recycled concrete aggregate as a base or subbase course, it is necessary to focus on its gradation, angularity, soundness, and solubility. Drainable bases require a different gradation than dense bases because drainable base gradations may require additional handling of fines waste to prevent clogging. Since the base provides the structure for a roadway, the soundness of the compacted RCA must be accurately discerned in order to ensure that RCA meets the load-bearing requirements of the pavement structure initially and in the long term. The angularity of RCA can increase the effort required to compact the granular material to dense base specifications. Some RCA can dissolve in the water passing through the pavement system. This dissolved material will raise the pH of the groundwater and may possibly affect vegetation within the vicinity of the road. When this water containing dissolved concrete meets the outside air, the carbon dioxide in the atmosphere will precipitate out calcium carbonate, which can potentially clog up a drainage system [6].

3. Problem statement and objective

A lot of old buildings in Egypt are collapsed or replaced yearly. As a result, the demolition and structure processes naturally introduce the problem of recycling materials where crushed concrete accounts for 60–70% of total debris production in Egypt. Despite that, there have been scarce studies concerned with the mechanical and durability properties of recycled aggregate used as base or subbase layer in Egypt. The main objective of this research is to better understand the mechanical behavior of recycled mixtures in order to evaluate whether they are feasibly useful as granular material in the base or subbase layer of road pavement. Moreover, RCA mixtures treated with cement are investigated to evaluate the improving range in mechanical performance. This study gains a great importance since landfills, and reclamation sites in Egypt will be exhausted in the near future. If recycled concrete aggregates can be reused as base or subbase materials, it will greatly alleviate the demand and extend the service life of the dumping facilities. To carry out these objectives, laboratory tests such as compaction proctor test, CBR, plate loading test, unconfined compressive test, and tensile strength are achieved. Many mechanical properties are obtained such as mixtures density, plastic deformation, resilient modulus, unconfined compressive strength, flexural strength, and indirect tensile strength. Moreover, this paper reviews the parameters that influence the mechanical properties of cement treated recycled aggregate (CTRA) such as RCA content, cement content, curing time, mixture dry density, fine material content in aggregate, and moisture content. Models to predict the unconfined and tensile strengths are established based on mixture parameters.

4. Literature review

4.1. Unbound recycled concert aggregate

Scientific knowledge on the potential for the use of recycled concrete aggregates in unbound road applications has advanced considerably. In Egypt and many countries and regions, however, the production of recycled concrete aggregate is much lower than the generation of mixed recycled aggregate obtained from the treatment of mixed rubble. This is made up of materials of various types, such as concrete, ceramics, asphalt, natural stone, as well as organic impurities (such as wood, plastic, and paper-cardboard), and inorganic impurities (metal and gypsum) [7]. Vegas et al. [7] constituted a scientific working document for regulating the use of recycled aggregates obtained from the treatment of mixed rubble in unbound structural road applications. In the short term, the intention was to continue this work by investigating the conditions of use of recycled aggregates of this type in bound applications with cement and lime, applying stricter criteria with regard to mechanical performance and durability.

Arulrajah et al. [8] considered a comprehensive laboratory evaluation of the geotechnical properties of five predominant types of construction and demolition (C&D) waste materials. The C&D materials tested were recycled concrete aggregate (RCA), crushed brick (CB), Waste Rock (WR), Reclaimed asphalt pavement (RAP), and Fine Recycled Glass (FRG). The geotechnical assessment included particle size distribution, particle density, water absorption, compaction, Los Angeles abrasion, post-compaction sieve analysis, flakiness index, hydraulic conductivity, and California bearing ratio (CBR) tests. Shear strength properties of the materials were studied through a series of triaxial tests. In terms of usage in pavement subbases, RCA and WR were found to have geotechnical engineering properties equivalent or superior to that of typical natural granular subbase materials. CB at the lower target moisture contents of 70% of the OMC was also found to meet the requirements of typical quarry granular subbase materials. The properties of CB, RAP, and FRG, however, may be further enhanced with additives or mixed in blends with high quality aggregates to enable their usage in pavement subbases.

Cerni et al. [9] provided a practical and innovative method for ranking granular material for pavement design on the basis of a performance-related approach such as permanent deformation analysis; on the other, they supported the use of construction and demolition materials as a sustainable and cost-effective alternative to traditional aggregates. Arulrajah et al. [10] investigated the recycled crushed brick when blended with recycled concrete aggregate and crushed rock for pavement subbase applications. The research indicates that up to 25%, crushed brick could be safely added to recycled concrete aggregate and crushed rock blends in pavement subbase applications. The repeated load triaxial test results on the blends indicate that the effects of crushed brick content on the mechanical properties in terms of permanent deformation and resilient modulus of both the recycled concrete aggregate and the crushed rock blends were marginal compared to the effects on dry density and moisture content.

Park [11] tested the physical and compaction properties of two different recycled aggregates obtained from a housing redevelopment site (RCA1) and a concrete pavement rehabilitation project (RCA2). The bulk specific gravity and water absorption values were 2.53% and 2.54% and 1.43% and 1.77% for RCA1 and RCA2, respectively. The optimum moisture contents were found to be 9% and 12.8%, and the corresponding dry densities were 2.21 and 1.81 Mg/m^3 for RCA1 and RCA2, respectively. It was apparent that the optimum moisture content increased with an increase in water absorption of the aggregates. Arulrajah et al. [12] achieved a laboratory investigation into the geotechnical properties of recycled concrete aggregate (RCA). The Los Angeles abrasion loss tests indicated that the RCA is durable. CBR values were found to satisfy the local state road authority requirements for subbase material. Repeated load triaxial tests established that the RCA would perform satisfactorily as a pavement subbase material in the field. The results of the laboratory testing undertaken in this research indicated that RCA satisfied the criteria for use in pavement subbase applications. Arulrajah et al. [13] indicated that, at a density ratio of 98% compared to maximum dry density obtained in the modified proctor test and with moisture contents in the range of 65–90% of the optimum moisture content, most of the recycled C&D materials produce comparatively smaller permanent strain and greater resilient modulus than natural commonly used granular subbase materials in pavement subbase applications.

According to Fabiana et al. [14], the possibility of using crushed concrete and demolition debris as subbase coarse aggregate was investigated. CBR experiments were conducted, and the behavior of the recycled materials was compared with the behavior of limestone. The results showed that CBR of crushed concrete was similar to that of natural aggregate. Conversely, demolition debris presented a fairly decrease in its CBR. Bozyurt et al. [15] demonstrated that the most common recycled construction materials used as unbound base course in pavement construction are recycled concrete aggregate (RCA) and recycled asphalt pavement (RAP). This study investigated the mechanical properties of RCA and RAP as unbound base, including the relationships between resilient modulus (Mr) and composition. The NCHRP model was more reliable in capturing Mr dependency on stress state in RCA and RAP. A multiple linear regression model was developed to predict the Mr of RCA ($R^2 = 0.96$) and RAP ($R^2 = 0.97$). There was a high degree of correlation between the predicted Mr and the physical properties of RCA ($R^2 = 0.89$) and RAP ($R^2 = 0.99$).

Jimenez et al. [16] in this article evaluates the behavior and environmental impact of two recycled aggregates from selected construction and demolition waste (CDW) in field conditions. For this purpose, one experimental unpaved rural road with two sections: the first using a mixed recycled aggregate and a recycled concrete aggregate and the second section consisted of crushed limestone aggregate as a reference. The results show that recycled aggregates from selected CDW can be used as an alternative to natural aggregates in unpaved rural road construction without risk of environmental impact. This study is important for increasing recycling rates and creating a market for mixed recycled aggregates in Mediterranean countries such as Egypt, which has one of the lowest recycling rates.

4.2. Cement treated recycled concrete aggregate

Cement treated materials, which are a family of compacted mixtures with granular materials, Portland cement and water, have been widely applied as road base/subbase pavements. Since 1915, when a pavement was constructed and compacted by using a mixture of shells, sand, and Portland cement, the materials treated by cement vary from coarse-grained aggregates, recycled aggregates to very fine-grained soils [17]. In practice, note that there are also other stabilizing agents to stabilize road materials. They are lime, granulated blast furnace slag, pozzolanas, bitumen, and chemical stabilizers. The literature review of previous researches has indicated that coarse-grained materials with low plasticity index are the most appropriate granulates for cement treatment where the cement treated granular materials have been used as semirigid base course [4].

Cement treated aggregate material (CTAM) herein is described as a mixture in which a relatively small amount of cement is used as a binder of coarse aggregates, and which needs a proper water content for both compaction and cement hydration. Generally, CTAM as a road base material is produced by using coarse natural or crushed aggregates and designed as a heavy traffic base or a heavy traffic wearing course. Recently, in order to protect the natural resource and reduce the environmental pollution of solid waste, recycling aggregates, such as crushed concrete and crushed masonry, have been considered to be used in road bases [5]. Hilmi et al. [18] utilized a traditional base material in road pavements treated with cement content of 2%, 4%, 8%, and 10% by total weight. They reported that the cement content was the most important parameter controlling the design life (fatigue performance) of stabilized layers. It should be stressed that layer thickness was also important on design life. Mixes having cement content less than 8% might be used as subbase materials instead of being used in pavement base.

Agrela et al. [19] investigated the use of mixed recycled cement treated aggregates to build the subbase and base layers of roads. They reported that compared with natural aggregates, mixed recycled aggregates had a low optimal density in the modified proctor test because of the increasing percentage of masonry particles. A greater amount of water was necessary to enable optimal compaction of cement treated mixed recycled aggregates in road subbases. Cement treated mixed recycled aggregates had a lower workability time, and thus, it might be useful to apply a setting retardant additive. Cement treated mixed recycled aggregates exhibited good mechanical performance in terms of adequate compressive strength, low deflections under impact load, and appropriate roughness values.

4.3. Tensile and compressive strength of recycled aggregate

Tensile strength is a very important geotechnical parameter to predict the cracking behavior of pavements, earth dams, and earth structures using stabilized soils. According to many researches, the tensile strength to unconfined compressive strength ratio was approximately 0.13 for lime stabilized soils. Kumutha and Vijai [20] reviewed that both unconfined compressive and tensile strengths for the stabilized soil (derived from weathered sandstone) treated with carbide lime and fly ash. They noticed that both tensile strength and unconfined compressive strength increased through curing time (7, 28, 90, and 180 days), and the ratio of tensile to compressive strength increased with long-term curing but with different rates.

5. Experimental program and research approach

This study presents a laboratory investigation aimed to characterize the behavior of recycled concrete aggregate compared with natural aggregate. The first part of research studies the mechanical characterization of unbound recycles base aggregate as well as traditional limestone aggregate to determine the optimum mixing ratio. The second part is entirely dedicated to study of the performance of cement treated recycled aggregate where a laboratory test program is developed through traditional geotechnical tests. The flow chart of the experimental study is presented in Fig. 1. To achieve the above stated objectives, different parameters are evaluated where each parameter is varied in the following manner.

(1) Recycled aggregate content in the mixtures: tests are made at (0.0%, 25%, 50%, 75%, and 100%) RCA.
(2) Cement content: the mixtures are designed by adding (4%, 5%, 6%, and 7%) Portland cement.
(3) Curing time: CTRA samples are tested within compressive test after curing periods of (1, 3, 7, 28 days).
(4) Mixture dry density: The effect of dry density variation due to different moisture contents on the UCS is evaluated.
(5) Moisture content: LSA mixtures are prepared with moisture content ranged from 6.5% to 11.0%, while RCA mixtures are prepared with moisture content ranged from 7% to 14.0%.
(6) Fine material amount: CTRA samples are prepared with different fine material amounts (5%, 9%, 12%, and 16%).

6. Materials

6.1. Natural aggregate

Limestone aggregate LSA taken from the general Nile company of desert roads is used in this research as granular layer material. The origin of the limestone aggregates is EL-Suez area, in the northeast Egypt. Fig. 2 illustrates the grading curves of LSA within the specification limits for highway works in the Egypt. LSA contains an amount of fines about 5% with 19% liquid limit and 14% plastic limit.

6.2. Recycled concrete aggregate

To produce RCA, Portland cement concrete is broken up and crushed. The major intrinsic material properties that limit the use of RCA are specific gravity, absorption, soundness (resistance to environmental conditions such as chemical and physical weathering), gradation, and contaminant solubility and the potential for groundwater contamination. The major external factors that limit the use of RCA are cost, state specifications, and environmental regulations [6]. The grain size distribution for RCA is presented in Fig. 2. The amount of fines in this aggregate reaches to about 4.8%.

6.3. Portland cement

Portland cement is used as a treatment material for the granular mixtures. The properties of this cement are given in Table 1.

6.4. Standards requirements for granular mixtures

The base/subbase courses must be made according to a specified aggregate gradation and requirements to insure adequate stability under repeated loads. Table 2 shows the different specifications required according Egyptian code for rural and urban highways.

7. Experimental work

7.1. Aggregate properties

The physical properties of the used natural and recycled aggregates are summarized in Table 3. The natural aggregates have the highest density value, while crushed concrete has the highest water absorption value. Indeed, the high amount of adhered mortar attached to RCA particle leads to a decrease in particle density and an increase in the water absorption.

7.2. California bearing ratio

CBR tests are performed on untreated compacted blended mixtures of RCA and LSA as a measure of granular soil strength. The mixtures are compacted in the test mold of 15.24 cm diameter and 12.7 cm height; moreover, 4.54 kg surcharge weight was applied.

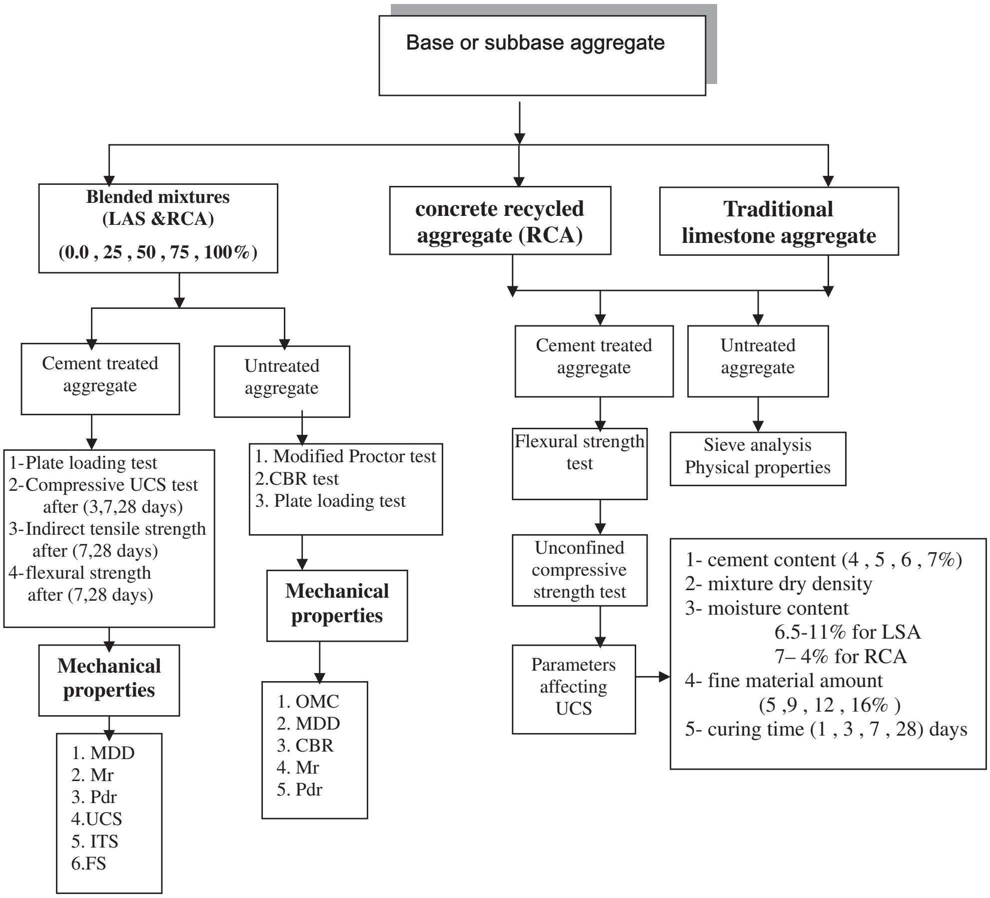

Figure 1 Flow chart of the experimental plan.

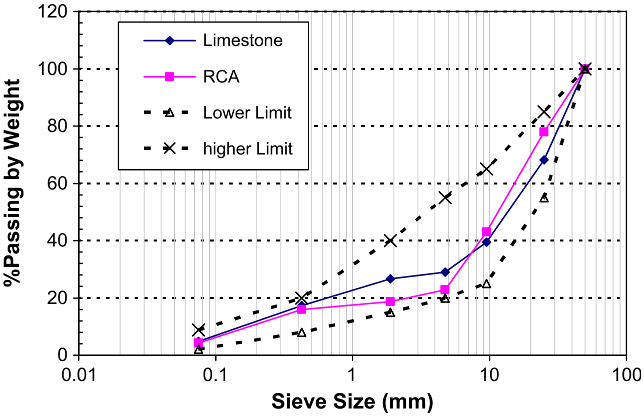

Figure 2 Grain size distribution for aggregates.

7.3. Plate loading test preparation

The test-model basically consists of a square iron box of $0.5 \times 0.5 \times 0.5$ m dimensions. The aggregate is spread in five layers of 10.0 cm thickness in the model and compacted manually by cylindrical concrete hummer weighted about 10 kg under OMC of each mixture. Then, sand cone test is carried out on the surface of the final compacted aggregate layer to check the relative density and make sure that it greater than 95% according to the standards of highways Egyptian Code. The surface of compacted aggregates is leveled; then, the loading circular steel plate of 16 cm diameter and 2.5 cm thickness is centered. A contact pressure of 0.5 N/mm^2 on asphalt surface layer is considered. Using the BISAR-linear elastic program, the vertical stress reaches to the base coarse considering 5.0 cm asphalt wearing coarse and 5.0 cm asphalt binder coarse decreases to 0.35 N/mm^2. The deflection under the vertical stress allowed to reach almost the maximum value after 30 min for each cycle. After that, the total load is released, and the material is allowed sufficient time to rebound. This cycle is repeated three times.

7.3.1. Resilient modulus

The resilient modulus obtained from the plate loading test is based on the elastic theory. When a rigid plate is put on the surface of the subgrade soil, the resilient modulus is as follows [21]:

$$\mathrm{Mr} = \frac{\pi(1-\mu^2)p \cdot a}{2w} \tag{1}$$

where Mr is the resilient modulus (Mpa); p the uniform applied pressure (Mpa); a the radius of circular plate (mm); w the deflection corresponding to the third load on the rigid plate test (mm); and μ is the Poisson's ratio of the aggregate.

7.3.2. Permanent deformation

To utilize current mechanistic–empirical methods of pavement design, material properties of the pavement system (pavement

Table 1 Properties of the Portland cement.

Properties	Value	Chemical properties	Value
Specific gravity	3.15	CaO (%)	58.32
Initial setting time (min)	150	SiO2 (%)	26.56
Final setting time (min)	185	MgO (%)	1.12
Volume expansion (mm)	2.0	Fe_2O_3 (%)	3.89
Compressive strength (MPa)		Al_2O_3 (%)	6.58
2 days	22.0	SO_3 (%)	3.32
7 days	38.7	LOI (%)	1.25
28 days	46.8	Specific mass (kg $10^3/m^3$)	2.96
		Specific surface area (mm^2/g)	39.78

Table 2 Egyptian code standards requirements for aggregate mixtures.

Sieve designation	% By weight passing square mesh sieve					
	Grading A	Grading B	Grading C	Grading D	Grading E	Grading F
2 in. (50 mm)	100	100				
1 in. (25 mm)		75–95	100	100	100	100
3/8 in. (9.5 mm)	30–65	40–75	50–85	60–100		
#4 (4.75 mm)	25–55	30–60	35–65	50–85	55–100	70–100
#10 (2 mm)	15–40	20–45	25–50	40–70	40–100	55–100
#40 (0.425 mm)	8–20	15–30	15–30	25–45	20–50	30–70
#200 (0.075 mm	2–8	5–20	5–15	10–25	6–20	6–25
Usage			For surface course			
	For bases and subbases					
Soil	Crushed stone, gravel, crushed sand and fine materials				Natural or crushed sand with fines with and without stone or gravel	
Components	% Sieve no. 200 > 2/3% passing no. 40 sieve					
Consistency	Liquid limit > 25 and plasticity index > 6					

Table 3 Properties of natural and recycled aggregates.

Property	RCA	Limestone	Egyptian standard
Unit weight (kg/m^3)	2546	2660	Relative density > 95%
Los Angeles abrasion (%)	33.5	40	50 max
Angle of internal friction (°)	47	23	–
Bulk specific gravity	2.4	3.1	ASTM C-127
Water absorption (%)	2.25	1.05	10 max
Poisson's ratio	0.25	0.35	–
Plastic index (PI)	3.5	5.0	Max L.L 30% Max P.L 8%

layer, base, subbase, and subgrade) are needed to analyze its response to traffic-type loading. Knowledge of material properties allows for the prediction of stresses and strains developed in the pavement system. For flexible pavement design, the prediction of failure is based on determining the plastic deformation in base layer. The plastic deformation for blended base aggregate mixtures can be obtained from the plate test after the third loading cycle.

7.4. Unconfined compressive strength

For cement treated mixtures, compressive strength tests (ASTM C 39) are conducted where the preliminary cement content by weight or by volume was selected. The unconfined compressive strength (UCS) values for aggregate mixtures are obtained by testing cylindrical specimens of dimensions 150 diameters with 300 mm height (length/diameter ratios of about 2.00) using steel molds. The cast specimens are kept in ambient temperature for 24 h; after that, the samples are wrapped in double layers of wet burlap where placed in moist environment for curing. The average unconfined compressive strength of the cement treated specimens after 1, 3, 7, and 28-days moisture curing time is obtained.

7.5. Tensile strength

The tensile strength of cement treated recycled aggregate is always considered as a significant material parameter for designing pavement structures. The reason is because the bottom of the treated aggregate layer suffers the tensile stress. In general, flexural beam tests and indirect tensile tests have been employed to evaluate the tensile strength of treated aggregate.

7.5.1. Flexural strength

Designers of pavement use a theory based on flexural strength (FS). Therefore, laboratory mix design based on flexural strength tests may be required. The flexural strength is expressed as modulus of rupture where determined by stander test method (ASTM C-78). For measuring flexural strength, normal standard size of specimens $150 \times 150 \times 500$ mm is used. Equal loads are applied at the distance of one-third from both of the beam supports. As loading increases, if fracture occurs within the middle one-third of the beam, the maximum tensile stress reached called "flexural strength" is computed from following equation [5]:

$$\mathrm{FS} = \frac{pl}{bd^2} \tag{2}$$

L is the beam span between supports; d the depth of beam; b the width of beam; and p is the rupture load.

7.5.2. Indirect tensile strength

The indirect tensile strength (ASTM C-496) is conducted. A standard test cylinder specimen (300×150 mm diameter) is placed horizontally between the loading surfaces of compression testing machine. Due to this compressive loading, an element lying along the vertical diameter is subjected to a vertical compressive stress which acting for about 1/6 depth. The larger portion of cylinder is subjected to uniform tensile stress acting horizontally which acting for about 5/6 depth. The indirect tensile strength (ITS) can be calculated from the following formula [22]:

$$\mathrm{ITS} = \frac{2P}{\pi DL} \tag{3}$$

L is the length of cylinder; D the diameter of cylinder; and p is the compressive load at failure.

8. Experimental results

8.1. Moisture–density relationship

Modified proctor compaction test (ASTM D698) is conducted on RCA and LSA blended mixtures. The maximum dry density (MDD) and optimum moisture content (OMC) are illustrated in Table 4. The natural aggregates have the highest MDD by about 10% and the lowest OMC. Since the grading of each aggregates is similar, this difference is mainly attributed to the physical properties of natural aggregates which has the highest particle density and is less porous. RCA has higher water content where can absorb nearly twice the amount of water compared with natural aggregate. This absorption can minimize water infiltration into and under highways that use RCA as road base material. This results agree with many researches [3,10,12].

8.2. California bearing ratio

CBR test is carried out in both unsoaked and 4-day soaked conditions where the results are summarized in Fig. 3. According to the highway Egyptian standards, the minimum CBR values for subbase and base courses are 25% and 50%, respectively. In unsoaked case, the LSA has the highest CBR value (85%) where the CBR value gradually decreases as the RCA content increases. One possible reason is the lower intrinsic particle strength of RCA which lead to a decrease in the overall bearing strength of the base or subbase materials. Furthermore, it can be seen from Fig. 3 that the influence of the 4-day soaked period is negligible on the CBR values. The result proves that the soaked CBR values for all recycled granular aggregate mixtures are greater than 30% where the recorded swells are less than 0.15% which can be considered negligible.

8.3. Plate loading test results

In the first load cycle, the cumulative deformation increases rapidly with increasing the vertical pressure. When the total load releases and the material takes a sufficient time to rebound, one part of vertical deflection is return and the residual part is remained as shown in Fig. 4 for limestone aggregate which considered as an example for the plate loading test results. The resilient modulus can be calculated after the third loading cycle from Eq. (1), where the uniform applied pressure (P) equals $0.35\ \mathrm{N/mm^2}$ and the radius of circular plate (a) equals 80 mm. As obtained in Table 5, the RCA has high resilient modulus more than LSA where with increasing the RCA content in the blended mixtures, Mr values increase. The optimal mixing ratio according to Mr is 75% RCA + 25% LSA.

Plastic deformation is related to the stiffness properties of the material that affect the fatigue cracking of overlying asphalt layers, whereas the gradual accumulation of permanent deformations, although very small during each loading cycle, could lead to the collapse of the structure due to excessive rutting. Therefore, the conventional road pavement design approach is based on providing adequate thickness of layers in such a way that the pavement structure does not experience shear failure and that unacceptable permanent deformations occur in each layer. On the basis of this evidence, an appropriate understanding and characterization of plastic deformation behavior of granular materials is needed in order to perform a successful pavement design [8]. Table 5 shows the total deformations as well as the plastic deformation ratios (Pdr) that means the accumulated plastic deformation divided on the total deformation after the third loading cycle. In fact, the 100% RCA sample donates minimal Pdr (45.5%). The addition of LSA to the RCA samples aides in increasing the amount of plastic deformation.

Table 4 Compaction test result for untreated mixtures.

Blended name	Materials	Optimum moisture content (OMC) (%)	Maximum dry density (MDD) ($\mathrm{t/m^3}$)
Mix RA0	100% LSA	11.0	1.984
Mix RA25	75% LSA + 25% RCA	9.5	1.900
Mix RA50	50% LSA + 50% RCA	10.6	1.820
Mix RA75	25% LSA + 75% RCA	12.3	1.780
Mix RA100	100% RCA	14.7	1.740

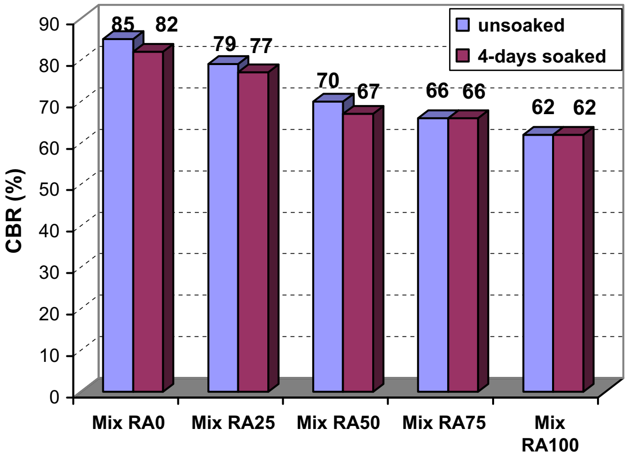

Figure 3 CBR test result for blended granular mixtures.

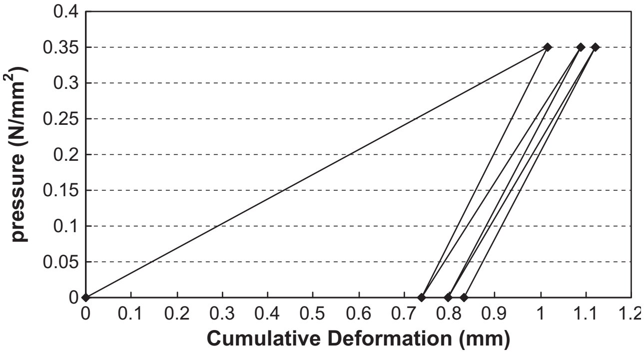

Figure 4 Cyclic loading test for limestone aggregate.

Table 5 Plate loading test results for granular blended mixtures.

Blended name	Total deformation (mm)	Plastic deformation ratio (Pdr) (%)	Mr (MPa) (N/mm^2)
Mix RA0	1.12	74.0	34.5
Mix RA25	1.08	66.5	39.3
Mix RA50	0.92	53.7	43.5
Mix RA75	0.82	48.3	49.5
Mix RA100	0.88	45.5	46.8

9. Cement treatment for coarse aggregate

The proportioning design method of cement treated recycled base aggregate CTRA mixture that applied in the last decades is tentative. Therefore, the problem of designing a CTRA mixture is the lack of an effective procedure that allows predicting its mechanical properties from mixture parameters like the mix composition and the characteristics of components [4]. This paper herein studies the influence of mixture variables on the mechanical properties of CTRA. The objective is to indicate the possibility for establishing an effective approach to predict the mechanical properties on basis of mixture parameters. Selecting the range of the preliminary cement content by weight or by volume, which is generally determined by the material type, is investigated by many studies as for example Arulrajah et al. [12] as shown in Table 6. According to the natural and recycled aggregate classification in this research, the cement is chosen to be added by 5% by the mass.

Coarse aggregates applied for treated granular layer should have some basic requirements such as a continuous grading, a coarse aggregate size and a good aggregate strength. The value of PI is also considered to determine whether or not the material is suitable for cement treatment. If the PI is high, the mortar will be soft and slippery under wet conditions. This could results in looseness of coarse particles which in turn may result in raveling [4].

9.1. Resilient modulus and plastic deformation for mixtures

The blended recycled aggregate mixtures are tested under plate loading test to obtain the resilient modulus and plastic deformation ratio Fig. 5 illustrates a valuable improvement in Mr values due to cement treatment where it shows that the improvement percentage (IV) increases as the RCA increases. The treated MixRA75 achieved the maximum Mr with IV reaches to 35%. The IV values due to decreasing the plastic deformation ratio Pdr are illustrated in Fig. 6. It clearly noted that the cement treatment leads to a great decreasing in plastic deformation where the maximum decreasing ratio (60.0%) is obtained at MixRA100. The cement treatment advantages in increasing the resilient modulus or decreasing the plastic deformation are clearly appeared at higher recycles aggregate adding content to natural aggregate.

9.2. Unconfined compressive strength

The UCS is generally acknowledged as an important indicator of the mixture quality of treated aggregate. A number of mixture variables influence its compressive strength are investigated such as the cement content, mixture dry density, moisture content, fine materials amount, and curing time.

9.2.1. Influence of cement content

Fig. 7 shows the influence of cement content on the UCS for LSA as well as RCA after 3 days curing period. A linear relationship may be given to approximate the relationship between the UCS and the cement content. It is clearly noted that RCA is more sensitive to the change in the cement content where it has a sharp curve more than LSA. This may be indicates that the UCS of concrete recycled aggregate treated with cement is obviously improved with increasing cement content. This crystallizes the importance of RCA usage as treated base course in improving its compressive strength compared with LSA, especially at higher cement content.

9.2.2. Influence of mixture dry density

The effect of the dry density after compaction due to different moisture contents on the UCS after 3 days curing period and cement content of 5% has been studied for both treated LSA and RCA and illustrated in Figs. 8 and 9. It has been found that the UCS increases with the increase in the dry density where the relation is basically linear and may therefore be expressed as a law:

$$\mathrm{UCS} = K + n(D) \tag{4}$$

Table 6 Cement requirements for different soil groups [12].

AASHTO group	A-1-a	A-1-b	A-2	A-3	A-4	A-5	A-6	A-7
Cement by mass (%)	3–5	5–8	5–9	7–11	7–12	8–13	9–15	10–16
Cement by volume (%)	5–7	7–9	7–10	8–12	8–13	8–13	10–14	10–14

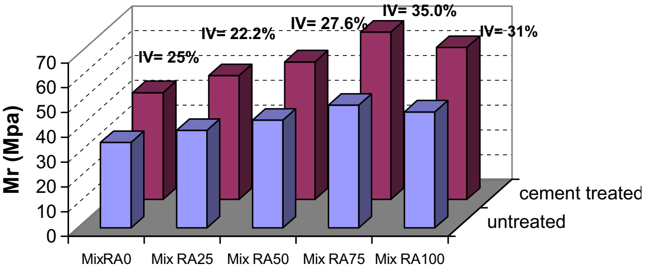

Figure 5 Resilient modulus results for RCA blended mixtures.

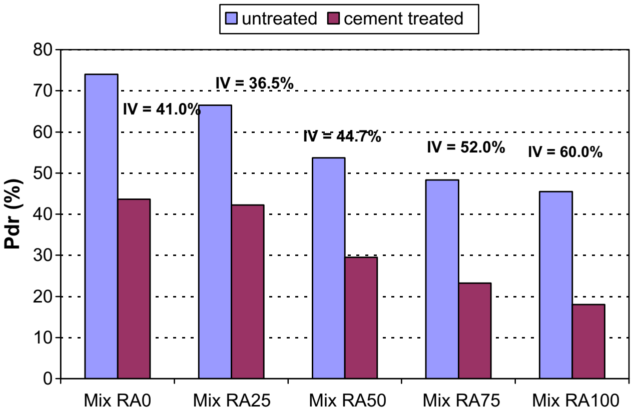

Figure 6 Plastic deformation results for RCA blended mixtures.

where D is dry density (kg/m^3); K is a constant; n is a dimensionless constant representing the tangent of the slop angle. In practice, the mixture density strongly depends on the degree of compaction where with the increase in the density, the UCS increases. That is one of the reasons that the UCS of treated natural aggregate is achieved by a high degree of compaction compared to recycled treated aggregate CTRA. As shown in Figs 8 and 9, the slop of the curve (n) is a function of the moisture where decreases with the increase in the moisture content for both LSA and RCA. Values of n for RCA are obviously higher than them for LSA.

Moreover, the effect mixing ratio between cement treated natural and recycled aggregates has been investigated. As shown in Table 7, the UCS increases and the density decreases with the increase in the RCA content. As reported in other studies [4,10,18], the lower density observed with increasing recycled aggregate content does not greatly affect the mechanical behavior of materials treated with cement. The maximum UCS value is obtained at MixRA75 where the natural limestone aggregates MixRA0 shows only about 68% compressive strength after 3 days when compared to the concrete recycled aggregate MixRA100. This percent increases to 77% and 90% with increasing the curing periods to 7 and 28 days, respectively. Based on the previous results, it can be said that although the low density may be compensated by increasing the RCA content, it is generally more economic to achieve high strength by a good compaction.

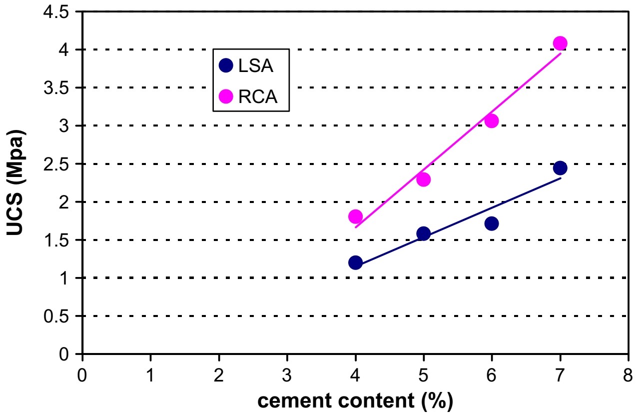

Figure 7 Influence of the cement content on the UCS.

9.2.3. *Influence of moisture content*

In order to explore the influence of the moisture content, the data in Figs. 8 and 9 are represented in Fig. 10. From the regression equations, the multiple R^2 for treated recycled aggregate with moisture content from 7.0% to 9.0% and treated limestone aggregate with moisture content from 6.5% to 11.0% are high. However, note that there is a big scatter for the regression equation of treated RCA when its moisture content ranges from 9.0% to 14% (R^2 = 0.7909).

9.2.4. *Influence of fine material amount*

The linear relationship shown in Fig. 7 is valid for one specific gradation. It means that other physical properties are not considered, such as aggregate strength and gradation [12,18]. Fig. 11 shows the influence the fines content (of grain size below 0.075 mm) for both treated RCA and LSA after 3 days curing period. It is generally observed that the approximate strength increases with increasing the cement content. RCA gets higher UCS more than LSA for each fine percent. It means that the linear slope between the UCS and the cement content is determined by the aggregate type and also the fines content. The computer program (Datafit9.0) is used for determining the unconfined compressive strength as a function in cement and fine contents. The following nonlinear relationship can be achieved:

$$\mathrm{UCS} = a \times F^b \times C^c \tag{5}$$

where UCS is unconfined compressive strength (Mpa); F is percent of fine content (%); and C is percent of cement content (%). The coefficients for traditional lime stone aggregate are (a = 0.066, b = 0.466, and c = 1.387 with R^2 = 0.932), while the coefficients for cement treated recycled aggregate are (a = 0.1257, b = 0.239, and c = 1.486 with R^2 = 0.90).

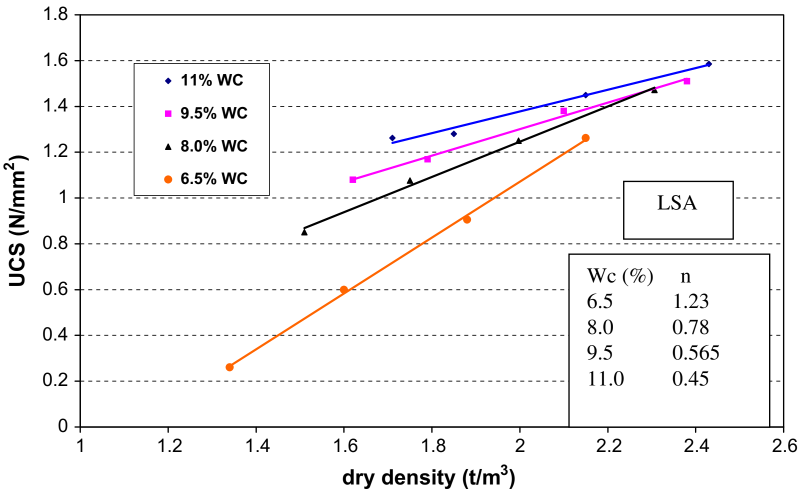

Figure 8 Relations between the UCS and the dry density for treated LSA.

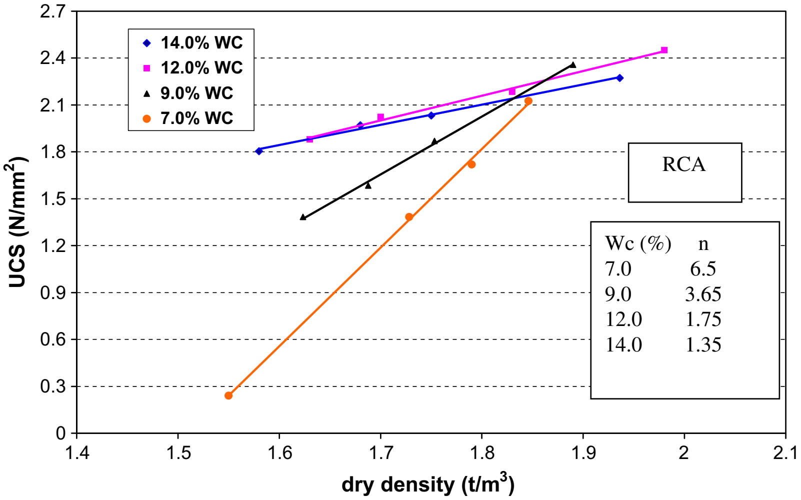

Figure 9 Relations between the UCS and the dry density for treated RCA.

Table 7 Relations between the UCS and the dry density for treated blended mixtures.

Blended treated Mix	Density 10^3 (kg/m^3)	UCS 3 days (N/mm^2)	UCS 7 days (N/mm^2)	UCS 28 days (N/mm^2)
Mix RA0	2.43	1.57	1.968	3.138
Mix RA25	2.32	2.46	2.46	3.32
Mix RA50	2.21	3.18	3.54	3.94
Mix RA75	2.08	3.40	3.65	4.12
Mix RA100	1.98	2.29	2.576	3.481

9.2.5. Influence of curing time

The curing age is another important factor affecting the UCS. The UCS development with the curing time at cement content 5% and fine amount 5% is shown in Fig. 12. It can be noted that the UCS approximately increases linearly with the curing time. A number of researches have reported its influence on the UCS [7,13,15]. For example, the relationship between the UCS and the curing time can be given as following Eq. (6) [3]:

$$f_c(t) = f_c(t_o) + k \cdot \log\left(\frac{t}{t_o}\right) \tag{6}$$

where $f_c(t)$ is the UCS at curing age of t days and $f_c(t_o)$ is the UCS at curing age of t_o days. Another adopted prediction model based on experimental data considering the influence of the curing time is as shown in following Eq. (7) [12] where this model brings two adjustable variables (a and b) for the UCS estimation.

$$f_c(t) = f_c(28)\frac{t}{a + b \cdot t} \tag{7}$$

where $f_c(t)$ is the UCS at time t and $f_c(28)$ is the 28-day UCS. Herein, the relationship between the UCS and the curing time

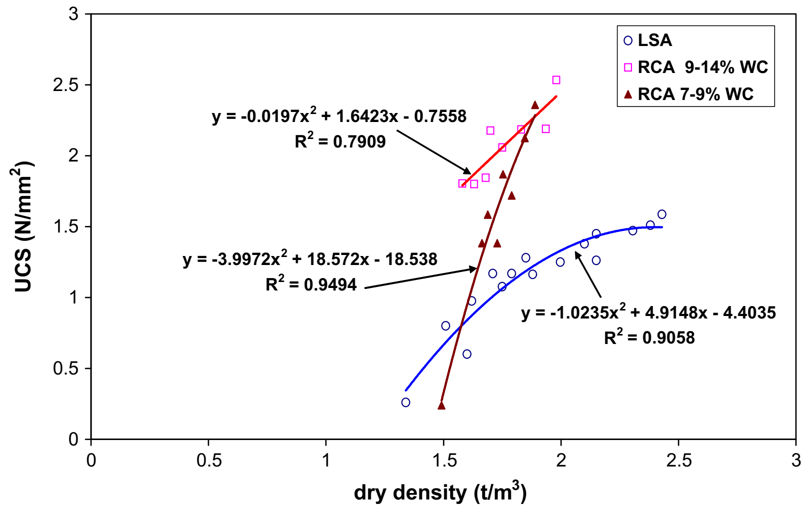

Figure 10 Influence of the moisture content on the UCS.

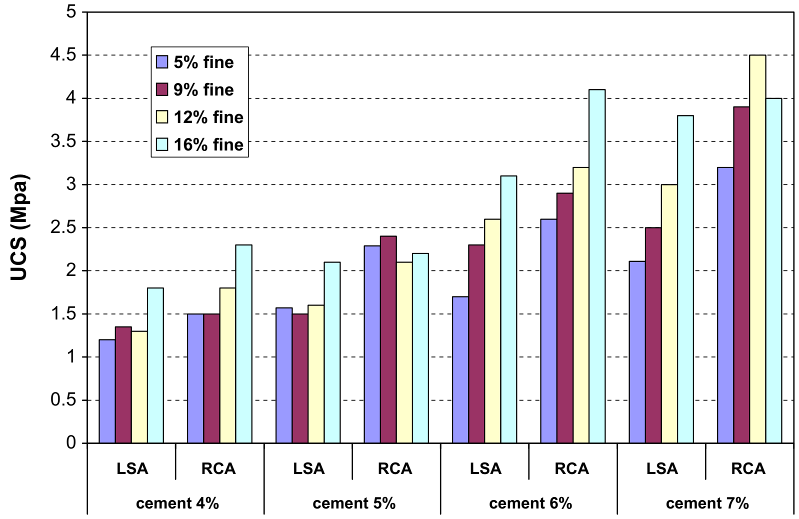

Figure 11 Influence of the fine material amount on UCS.

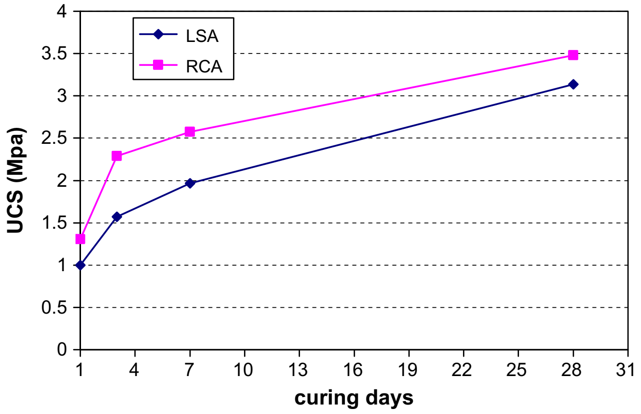

Figure 12 Influence of the curing time on the UCS.

is illustrated in the following Eq. (8) where this model brings three adjustable variables (a, b and c). The coefficients for traditional limestone aggregate are $a = 1.01$, $b = 1.011$, and $c = 0.33$ with $R^2 = 0.99$, while the coefficients for cement treated recycled aggregate are $a = 1.236$, $b = 1.068$, and $c = 0.247$ with $R^2 = 0.95$.

$$\mathrm{UCS}(t) = a \times (b)^{\mathrm{UCS}(28)} \times (t)^{c} \tag{8}$$

where UCS(t) is the unconfined compressive strength (Mpa) after curing time t (day).

9.3. Tensile strength results

9.3.1. Flexural strength

For flexural strength, which is an important material parameter when designing pavement where it has been shown from previous literatures that the flexural strength (FS) of CTRA are about 10–20% of the UCS [7]. Fig. 13 illustrates the relation between UCS and FS considering fine amount of (5%, 9%, 12% and 16%) for both 5% cement treated LSA and RCA after 7 and 28 days curing period. From results, it can be noted that with the increase in fine content, the ratio of FS to the UCS increases within limits from 10% to 20%. This implies that the material skeleton influences the flexural strength. Furthermore, For LSA, the ratio of FS/UCS is larger (up to 20%) than it for

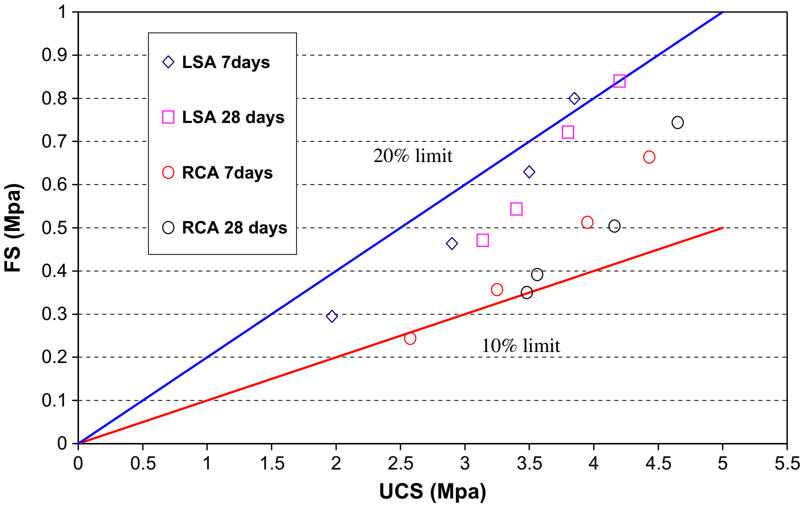

Figure 13 Flexural strength plotted against the UCS.

Table 8 Flexural and indirect tensile strengths.

Blended treated mixtures	Curing days	Indirect tensile strength (ITS) (MPa)	Flexural strength (FS) (MPa)	FS/UCS (%)
Mix RA0	7	0.242	0.295	14.5
	28	0.42	0.471	15.0
Mix RA25	7	0.238	0.281	11.4
	28	0.376	0.452	13.6
Mix RA50	7	0.232	0.272	7.6
	28	0.357	0.428	10.8
Mix RA75	7	0.225	0.265	7.3
	28	0.322	0.41	10.0

RCA (down to 10%) where the recycled aggregate shows about 75–80% of the strength of natural aggregates. On the other hand, the curing period has no obvious effect on the ratio of FS/UCS. An approximate relationship between FS and UCS can be given by following Eq. (9) where the coefficients for LSA are ($a = 0.26$ and $b = 0.271$ with $R^2 = 0.92$) while for RCA are ($a = 0.24$ and $b = 0.428$ with $R^2 = 0.93$):

$$\mathrm{FS} = a(\mathrm{UCS}) - b \tag{9}$$

If the fine amount (F) is considered, the relation can be expressed as following Eq. (10), where the coefficients for LSA are ($a = -0.128$, $b = 0.154$, and $c = 2.0$ with $R^2 = 0.983$) while for RCA are ($a = -0.404$, $b = 0.28$ and $c = 0.019$ with $R^2 = 0.96$).

$$\mathrm{FS} = a + b \times (\mathrm{UCS}) + c \times (F) \tag{10}$$

Considering these test results shown in Table 8, it is remarkable that with increasing the recycled aggregate content or decreasing the curing period, the flexural strength as well as the ratio (FS/UCS) obviously decreases.

9.3.2. Indirect tensile strength

The indirect tensile strength (ITS) is calculated according to Eq. (3) for blended granular mixtures treated with 5% cement. As shown in Table 8, concrete recycled aggregate shows only about 70% strength when compared to natural limestone aggregates. Moreover, with increasing the recycled aggregate in the mixture, the ITS decreases.

9.4. Conclusions

Most recycled aggregates produced in Egypt contain large amounts of crushed concrete. Thus, detailed research on the application of recycled cement treated aggregates to build the subbase or base layers of roads is therefore needed. It is found that the mechanical properties of cement treated mixtures are influenced and determined by a number of variables, including cement content, curing time, and fine material amount. Based on the laboratory test results, the following conclusions are drawn:

1. With increasing the concrete recycled aggregate to natural limestone aggregate, the maximum density and CBR values of untreated mixtures decrease and the optimum moisture content increase. The soaked CBR values for recycled aggregate lie within Egyptian allowable limits. Moreover, the concrete recycled aggregate mixtures donate minimal plastic deformation while the maximum resilient modulus is achieved at MixRA75. The cement treatment leads to a valuable improvement in the resilient modulus reaches to 35% at MixRA75 and in plastic deformation reaches to 60% at MixRA100.
2. A linear relationship can be given to approximate the relationship between the UCS and the cement content where the UCS of concrete recycled aggregate is obviously higher than it for limestone aggregate especially with increasing cement content. The dry density or the degree of compaction is an important factor to determine the UCS of treated

aggregate where a linear relation correlates them. The UCS increases, while the density decreases with the increase in the RCA content.

3. There exists a threshold moisture content (9%) that critically influences the UCS development of CTRA. Up to this moisture content, a strong regression equation is achieved between dry density and UCS. Beyond this level a big scatter for the regression equation is obtained. On the other hand, the UCS approximately increases linearly with the curing time for both treated recycled and natural aggregates. The relationship between them is illustrated with three adjustable variables thus it produces more accurate estimation.
4. With the increase in fine material amount, the strength ratio (FS/UCS) increases within limits from10% to 20%. The LSA obtains strength ratio higher than it for RCA where the recycled aggregate shows about 75–80% of the flexural strength for natural aggregates and about 70% of the indirect tensile strength for natural aggregates. The curing period has no obvious effect on the strength ratio. Generally, the building demolition debris in the base or subbase layers can be transformed into useful recycled aggregate through proper processing for pavement designs.

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