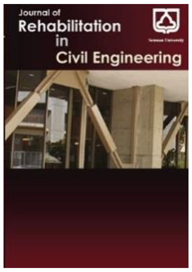
Journal of Rehabilitation in Civil Engineering 11-2 (2023) 131-152



Journal homepage: http://civiljournal.semnan.ac.ir/

Characteristics of Recycled Concrete Aggregate and its Implementation for Pavement Base Applications: a Review

Shravan Kumar Gangu[1*], Shankar Sabavath[2]

1. Research Scholar, Department of Civil Engineering, Transportation Division, National Institute of Technology, Warangal-506004, India.
2. Assistant Professor, Department of Civil Engineering, Transportation Division, National Institute of Technology, Warangal-506004, India.

Corresponding author: ss@nitw.ac.in

ARTICLE INFO

Article history:
Received: 30 June 2021
Revised: 02 July 2022
Accepted: 03 July 2022

Keywords:
Recycled concrete aggregate;
Stabilization;
Mechanical properties;
Environmental safety.

ABSTRACT

Significant amounts of Natural Aggregate (NA) materials are being used to meet the requirements of pavement structure. Simultaneously, enormous amounts of demolition waste, such as demolished concrete and reclaimed pavement materials, are dumped into landfills along roadsides, creating pressure on the environment. Therefore, the recycling of demolished materials and their utilization for pavement construction would result in conservation of natural aggregates, this would alleviate the problems related to geo-environment and bring several benefits for the environment and ensure sustainability. Several studies have been carried out to describe the mechanical properties of recycled concrete aggregate (RCA) with and without stabilization. A thorough understanding of performance-related engineering properties of unbound RCA and stabilized RCA is essential for mechanistic-empirical pavement design. This paper reviewed the mechanical properties such as compaction, California bearing ratio, resilient modulus, and permanent deformation in the case of unbound RCA, and unconfined compressive strength, flexural strength, and stiffness for stabilized RCA from accessible works of literature on the application of RCA for pavement base. The findings from the literature indicated that RCA is source-dependent, moisture sensitive, and subjected to particle breakdown under wheel load that results in reduced shear strength. Further, if RCA is treated with mechanical stabilization by geosynthetics, the interface shear strength properties improve, and permanent deformation is reduced. Chemically stabilized RCA is a promising technique as its strength and durability complied with stabilized NA. Therefore, this review will be helpful for pavement engineering practitioners to explore RCA use in pavement base or subbase layers.

How to cite this article:
Gangu, S. K., & Sabavath, S. (2023). Characteristics of Recycled Concrete Aggregate and its Implementation for Pavement Base Applications: A Review. Journal of Rehabilitation in Civil Engineering, 11(2), 131-152.
https://doi.org/10.22075/JRCE.2022.23836.1523

1. Introduction

Pavements are subjected to wheel loads from vehicular traffic. The long life of a pavement is possible only if the wheel load is appropriately distributed. Strength properties of aggregate materials against wheel load will determine the stability of the pavement base. If properly characterized and designed, the base and sub-base layers reduce the distress of rutting and fatigue in the asphalt layer. Vast quantities of natural aggregate (NA) are consumed every year to meet the requirements of pavement construction and maintenance activities. This has put a severe burden on natural resources with many countries facing an acute shortage of quality aggregates. The mere crushing of rock sources to create aggregates leads to significant ecological and environmental problems [1].

The gradual rise in urbanization and the growing economy have led to an increase in construction. Consequently, the construction of new infra projects is preferable to improving existing ones and this has resulted in a significant increase in demolition waste [2]. To keep pace with the demand for construction and pronounced environmental problems of construction demolition waste (CDW), it is essential to look at using recyclable alternative materials. Therefore, the recycling of CDW has gained significant attention worldwide [3-4]. Among the components of CDW, a substantial percentage of concrete debris is obtained from the demolition of concrete structures such as concrete pavements, bridges and buildings as shown in Fig. 1. Commonly, this concrete waste is transferred to landfills and along roadsides, which creates pressure on the geo-environment [5]. The recycling and reuse of concrete waste can be a successful way to attain sustainability by using recycled concrete aggregate (RCA) wherever it is technically, economically, and environmentally justifiable [6].

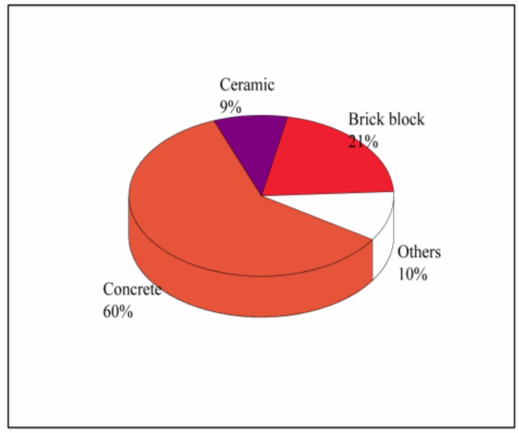


Fig. 1. Distribution of CDW [7].

In pavement construction, research has been undertaken to explore the possibility of using RCA obtained from demolished concrete as a substitute to natural quality aggregate (NA)s [8-16]. RCA mainly contains NA and adhered mortar. RCA's mechanical properties and performance have been in question because of the uncertainty in characteristics and fundamental variability in material sources.

There is minimal work documented on the application of RCA in pavement construction in developing countries like India. The direct employment of RCA as a substitute to NA in pavement base is not rational, as it may or may not indicate a similar response to moving wheel load traffic to that of the NA. This is because of the unusual particle size, shape, and variability in the source. Therefore, insufficiency may be tackled generally by stabilization.

Stabilization is the most approved technique to improve the mechanical and durable properties of alternative materials like RCA. Mechanical and chemical stabilization techniques are employed for pavement construction and maintenance because they are fast, efficient, and reliable [17]. Various researchers have used stabilization methods to upgrade the performance characteristics of RCA, using Portland cement, geo-polymers, fly ash, lime kiln dust, cement kiln dust, lime and bitumen emulsion [18-23].

Nwakaire et al. [24] carried out a literature review on the utilization of RCA for pavement applications such as subgrade, subbase, base, surface material, and concrete surfacing. The properties of RCA in each region are distinctive. This is because of non-identical concrete strength, several sources of quality and nature of NA, varied geological conditions of regions, dissimilar grading of RCA and so forth. Therefore, it is wise to use RCA in foundation layers, as pavement base and subbase require a large amount of NA if technically feasible. Sangar et al. [25], presented the review on RCA leachate. Aytekin and Aghabaglou [26] conducted a literature review on compaction, resilient modulus, permanent deformation characteristics of RCA as a base or subbase material. However, previous literature did not comprehensively present RCA's mechanical properties required for mechanistic-empirical pavement design as an unbound and stabilized pavement base material. Therefore, this paper aims to summarize the characteristics of RCA with and without stabilization for pavement base or subbase applications. This review will be helpful for pavement engineering practitioners to explore RCA use in pavement base or subbase layers.

2. Characteristics of RCA

2.1. Physical Characteristics

The performance of RCA is determined by the amount of adhered mortar, which depends on the properties of original concrete [27]. RCA shape is influenced by the method and level of crushing, as it contains varying amounts of mortar. Therefore, it is necessary to determine the properties of RCA with respect to pavement applications. Therefore, before any aggregate can be used for pavement construction, it needs to be tested using standard test procedures recommended by road authorities. The same kind of test characteristics will be conducted on any nonconventional material like RCA. The relevant elements include particle size distribution, shape, specific gravity, water absorption, density, hardness, toughness, and soundness.

Particle size distribution (PSD) is a fundamental physical property that influences pavement quality and performance. The PSD of RCA indicated that NA had more fines than RCA [13,28-29]. The difference in gradation of recycled concrete materials is attributable to differences in the crushing operations and the strength of original concrete [12]. The PSD of RCA may have a wide range due to differences in crushing methods [29]. The PSD of RCA considered in earlier studies was presented in Fig. 2. The particle density of RCA varied considerably between 2g/cc to 2.65g/cc, and this variation was due to the surface of aggregate coated with adhered mortar. In addition, RCA was porous and experienced a high degree of deformation [30]. According to Edil [29], the water absorption values of RCA ranged between 5.5 to 6.9% and was found to be more than that NA of 3%. Water absorption varied with aggregate size; coarse RCA was found to be less than fine RCA. This shows that water absorption would change with different gradations. The flakiness index of RCA was 40% by mass and it was recommended not to use flaky materials and the Los Angeles abrasion loss for RCA was 28%, less than 35% of local road authorities [13,30]. Table 1. shows the physical properties of RCA reported by several authors.

2.2 Compaction Characteristics

Generally, soils used in road bases are compacted to dense states to yield complacent engineering properties which include shear strength and compressibility. The optimum moisture content (OMC) required to achieve maximum dry density (MDD) for RCA is slightly higher compared to that of typical quarry material [13], which may be due to high water absorption of crushed concrete particles. In addition, the presence of mortar in RCA resulted in water absorption and required a higher amount of water to achieve maximum dry density for RCA than NA [29]. The results of the compaction test reported by several authors are presented in Fig. 3.

2.3 California Bearing Ratio

The California Bearing Ratio (CBR) test is a widely accepted empirical test for aggregates that pavement engineers have used to characterize the bearing capacity under traffic. It is an indirect measurement of shear strength and mainly depends on OMC, MDD and the level of compaction [31]. CBR value increased by 24% with an increase in proctor density from 95-99% [32]. CBR property of granular material for pavement design has become very limited as it does not simulate the field condition, and it can be used to select a material [33]. The influence of 4-day soaking had negligible effect on CBR value [34].Table 2 gives the CBR for RCA.

Table 1. Physical Properties of Recycled Concrete Aggregates.

Properties	**Author and Year**				
	[13]	[28]		[29]	
		ARR	**RCO**	**Average**	**Range**
% Fines	3.6	5.0	7.0	5.05	2.01-12.8
% Gravel	50.70	-	-	46.19	32-69
Coefficient of Uniformity (Cu)	31.2	-	-	24.60	8-45
Specific gravity	2.31	-	-	2.31	2.2-2.4
Water absorption (%)	4.7-9.8	8.9	5.5	5.52	5.5-6.9
Mortar content (%)	-	-	-	50.0	37-65
USCS Classification (ASTMD 2487)	GW	GW-GM	GW-GM	SP, GP, GW	
		A-1-a	A-1-b	A-1-a, A-1-b	
Flakiness Index (%)	11.0	-	-	-	-
Los AngelesAbrasio value (%)	28.0	39.0	37.0	-	-
ARR: Adelaide resource recovery; RCO: Resource Co.					

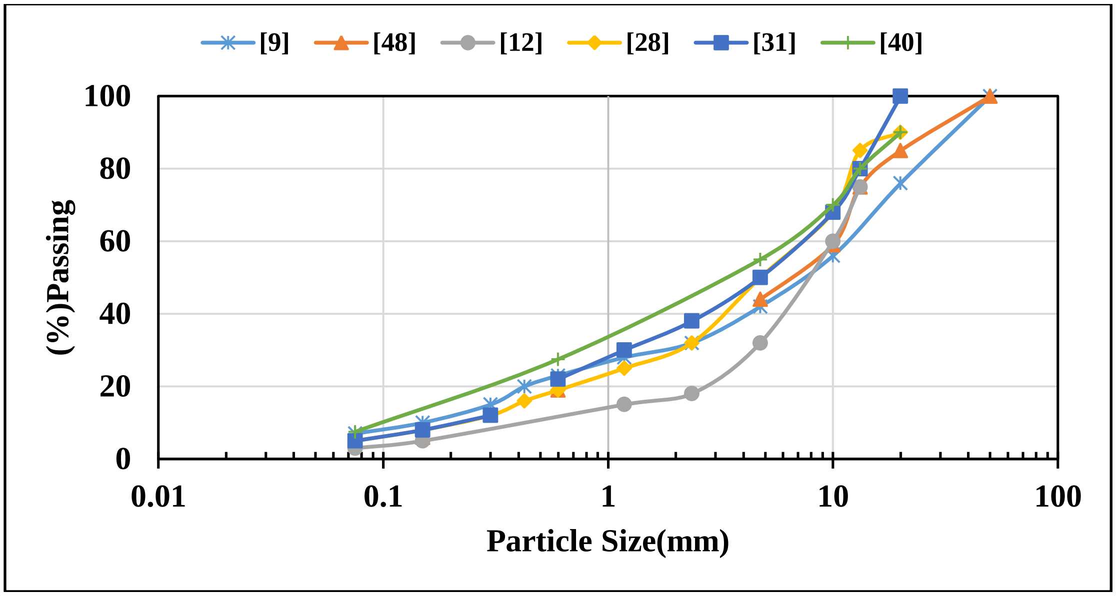


Fig. 2. Particle size distribution of RCA for base applications used by several authors.

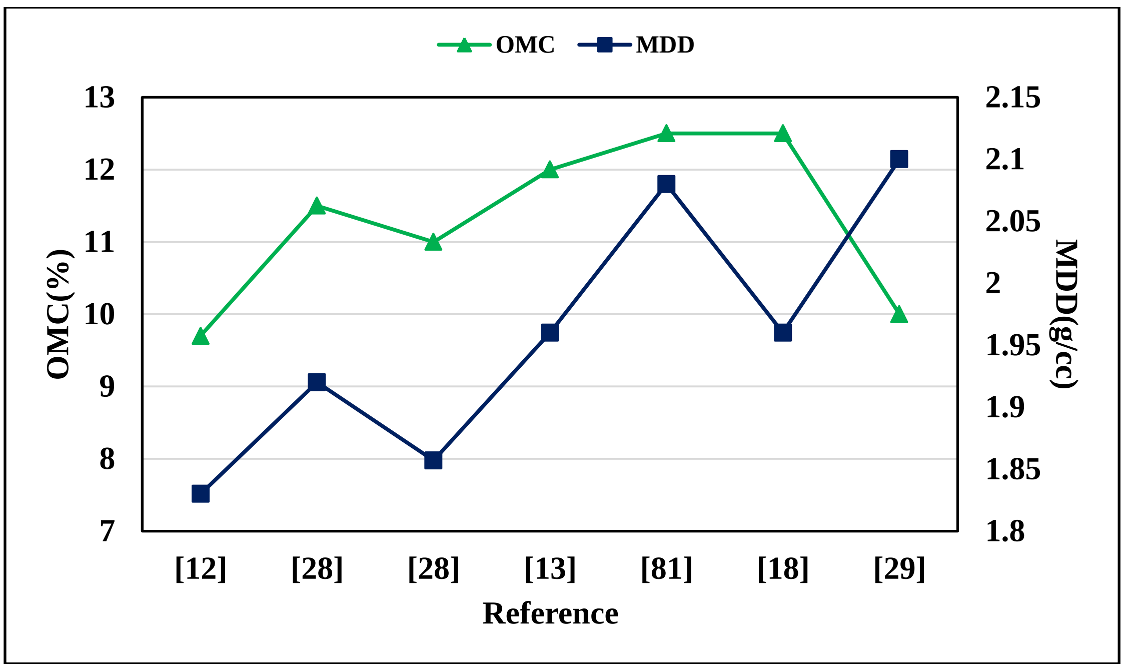


Fig. 3. Compaction characteristics of RCA.

Table 2. CBR values for Recycled Concrete Aggregates.

Reference	CBR (%)		Test Method
	NA	RCA	
[35]	83	66	BS1377-4
[36]	182	169	-
[37]	-	128	NF 94-078
[38]	152	97-138	UNE-EN 103502
[39]	85	62	
[40]	68	148	
[41]	256	242	UNE-EN 103502

2.4. Resilient Modulus (MR) and Permanent Deformation

The resilient modulus (M_R) is the elastic modulus used as an important input for mechanistic-empirical pavement design. Therefore, M_R has been considered as a means of characterizing the elastic properties of pavement materials. It is known that most paving materials are not elastic but experience some permanent deformation after each load application [42]. However, when the load is small compared to the strength of the material and repeatedly applied, the deformation under each repetitive load is recoverable and can be considered elastic. The pavement responses to be determined using multilayer elastic analysis depend on the constitutive model representing the material's resilient modulus behavior. The laboratory test for the base material under consideration will provide data for constitutive modeling of M_R behavior over a range of applied stress. The Repeated Load Triaxial Test (RLTT), following several testing procedures such as American Association of State Highway and Transportation Officials AASHTO TP46-94[43], AASHTO T307-99 [44], and National Cooperative Highway Research Program NCHRP 1-28A [45], is used to determine the M_R of pavement materials.

M_R is a function of several parameters: stress level, density, moisture content, gradation, fines content, aggregate type, and the number of load applications [46]. Many researchers have investigated the resilient behavior of RCA. For example, Bennert et al. [9] evaluated M_R and permanent deformation of RCA for base and subbase applications by cyclic triaxial test. The author reported that a blend of 25% RCA with 75% NA would obtain the same resilient behavior as Dense Graded Aggregate Base (DGAB) material for base and subbase layers. However, RCA material can present higher M_R values than DGAB as shown in Fig. 4. This is explained by a higher angle of internal friction, which contributes to improving shear resistance. A study conducted by Aydilek et al. [47], stated that M_R of RCA was 2.6 times greater in OMC condition and 2 times greater in MDD condition. Further, stiffness was found to increase with an increase in bulk stress during the freeze-thaw cycle. Fig. 5, shows that 100%RCA and 100% graded aggregate base (GAB) material gives higher values than RCA and GAB mixtures. This may be due to poor packing of particles or change in particle size distribution among the mixtures. Nataatmadja and Tan [48] established that M_R of RCA could be influenced by the compressive strength of parent concrete and the aggregate shape. The study concluded that M_R of RCA is comparable with typical virgin road aggregates.

Molin et al. [49] performed the resilient modulus test on RCA from several compressive strengths, 7, 30, and 73 MPa compared to NA. The M_R of low strength RCA was found to be 14% less than that of NA. High strength RCAs exhibited similar performance compared to normal strength RCA which showed excellent resilient moduli that was about 45% greater than NA. The permanent deformations were found to be 0.65%, 2.30%, 0.35% and 1.10% for samples at NA, 7MPa, 30MPa and 73Mpa.

Jitsangiam et al.[50] conducted RLTT on RCA and crushed rock base material molded at optimum moisture content and maximum dry density using the procedure specified by Vuong & Brimble[51]. The study's outcome indicated that M_R of RCA is approximately equal to that of crushed rock base. Arulrajah et al.[13] highlighted the importance of compaction and noticed high M_R at a density ratio compacted to 98% of modified proctor MDD and also noticed that RCA resulted in higher limits of permanent strain and lower limits of M_R at moisture contents less than OMC and this indicates RCA is susceptable to moisture.

Gabr and Cameron [28] compared the M_R of RCA with that of quartzite aggregates and found the behavior of RCA at 60% of OMC. Bozyurt et al.[52] demonstrated that RCA could be used as an unbound base by conducting M_R tests on RCA as per NCHRP protocol and reported that the NCHRP model was more reliable in capturing M_R dependency stress state in RCA. There was a high correlation between M_R and index properties of RCA. The models presented in Table 3, except S.No.5, are based on subgrade soils and virgin aggregates and not for recycled products. Azam, Cameron, and Rahman [53] found that initial matric suction affects behavior such as shear strength and resilient modulus of unbound granular materials. Further, the study recommended that matric suction should be considered as a factor in predicting resilient modulus.

The mechanistic-empirical pavement design guide [54] suggests model number 8 presented in Table 3 to predict M_R values for subgrade soils and virgin aggregates. This model considers that pavement materials are typically compacted to OMC and MDD. The range of k_1 and k_2 for RCA is presented in Table 4, and for NA in Table 5. Rutting is another crucial parameter for mechanistic-empirical design. It is the distress that reduces the performance of unbound pavement material. Bennert et al. [9], found that permanent deformation results indicated that 25% RCA mixed with 75% DGAB material obtained the lowest amount of permanent deformation when the material was cyclically loaded to 100,000 cycles. Arulrajah et al.[13] mentioned that the strain development of RCA at 60% of the OMC was minimum.

Further studies conducted by Arurajah et al. [55], revealed that adhered mortar on RCA affected the shrinkage and reflective cracks in compacted RCA. Haider et al. [40] concluded that RCA material showed more significant permanent deformation than Rockville Graded Aggregate Base (GAB) material under constant loads. However, RCA materials showed similar geo-mechanical and performance to conventional GAB material. Bestgen et al.[56] reported that virgin granular aggregate base materials showed lower permanent deformation than RCA. Arisha et al.[15], reported that the predicted M_R was greater than the South Australian specified value of 300MPa corresponding to the anticipated field stress and they recommended the use of RCA as an alternative to unbound base material. Jaykody, Gallege, and Ramanujam [57] showed that plastic strain was not influenced by moisture content above OMC; at lower confining stress, the principal stress was found to be dominant on the accumulated strain.

Table 3. Resilient Modulus prediction models used for RCA.

S.No.	Reference	M_R Test Protocol	Model
1.	[9]	AASHTO TP 46-94	Bulk Stress Model: $M_R = k_1\theta^{k_2}$
2.	[40]	AASHTO T307-99	Pezo Model: $M_R = k_1 p_a \left[\frac{\sigma_3}{p_a}\right]^{k_2} \left[\frac{\sigma_d}{p_a}\right]^{k_3}$
3.	[48]		Bulk Stress Model: $M_R = k_1 * \theta^{k_2}$
4.	[52]	NCHRP 1-28a	Witczak Model : $M_R = k_1 p_a \left(\theta - \frac{3k_6}{p_a}\right)^{k_2} \left(\frac{\tau_{oct}}{p_a} + k_7\right)^{k_3}$
5.	[53]	AUSTO 2007	$M_R = K_0 \left(\frac{\sigma_m}{p_a}\right)^{k_1} \left(\frac{\tau_{oct}}{\tau_{ref}}\right)^{k_2} \left(\frac{u_m}{p_a}\right)^{k_3} \left[\frac{DDR * \left(1 - \frac{k_4 *}{1}\right.}{100}\right.$
6.	[56]	AASHTO T 307-99	Pezo Model: $M_R = k_1 p_a \left[\frac{\sigma_3}{p_a}\right]^{k_2} \left[\frac{\sigma_d}{p_a}\right]^{k_3}$
7.	[58]	AUSTO 2007	Bulkstress Model : $M_R = k_1\, \theta^{k_2}$
8.	[54],[15]	AASHTO T 307(2012)	MEPDG Model: $M_R = k_1 p_a \left(\frac{\theta_b}{p_a}\right)^{k_2} \left(\frac{\tau_{oct}}{p_a} + 1\right)^{k_3}$

M_R-Resilient modulus; pa-Atmospheric pressure,
τ_{oct} - Octahedral shear stress $= \frac{1}{3}\sqrt{\{(\sigma_1 - \sigma_2)^2 + (\sigma_1 - \sigma_3)^2 + (\sigma_2 - \sigma_3)^2\}}$
σ_d=Deviatoric Stress, ($\sigma_d = \sigma_1 - \sigma_3$) ; σ_1 = Axial stress, σ_2= Lateral stress ($\sigma_2 = \sigma_3$), σ_3=Confining pressure,
Θ or Θ_b- Bulk stress = $\sigma_1 + \sigma_2 + \sigma_3 = \sigma_d + 3\sigma_3$;
DDR-Dry density ratio; u_m-Matric suction; RCM- Reclaimed Masonry. k_i-Multiple Regression Constants

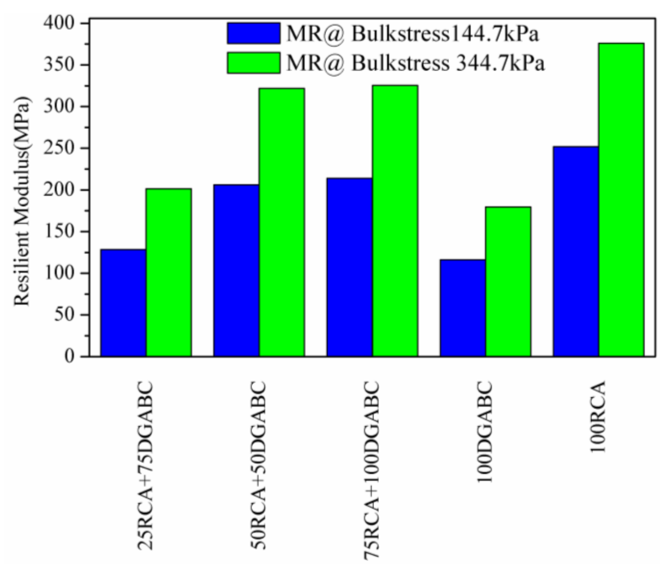


Fig 4. Comparison of Resilient modulus for RCA and DGABC mixes at different bulk stress [9].

Table 4. Range of k_1 and k_2 for untreated RCA by several authors.

Reference	Material	k_1 (MPa)	k_2	k_3
[9]	100% DGABC	9.553	0.5021	-
	75%DGABC+25%RCA	9.746	0.5184	
	50%DGABC+50%RCA	16.12	0.5124	
	25%DGABC+75%RCA	19.26	0.484	
	100%RCA	25.35	0.461	
[48]	AF RCA	10.387	0.594	-
	18.5MPa RCA	16.712	0.551	
	49MPa RCA	13.809	0.610	
	75MPa RCA	14.338	0.551	
	Dry Rhyolite	5.104	0.67	
[28]	ARR at 90% of OMC	25.1	0.48	-
	ARR at 80% of OMC	25.5	0.47	
	ARR at 60% of OMC	69.5	0.38	
	RCO at 90% of OMC	7.2	0.63	
	RCO at 80% of OMC	10.2	0.58	
	RCO at 60% of OMC	190	0.22	
	VA at 90% of OMC	7.4	0.58	
	VA at 80% of OMC	3.5	0.74	
	VA at 60% of OMC	6.5	0.66	
[40]	Rockville-(R)	1025	0.88	-0.22
	RCA-(A)	355.8	1.40	-0.18
	25%A+75%R	1430	0.82	-0.20
	50%A+50%R	356.50	1.54	-0.17
	75%A+25%R	478.1	1.45	-0.34
	RCA-(B)	493.3	1.18	-0.13
	25%B+75%R	510.61	1.29	-0.18
	50%B+50%R	450.63	1.27	-0.11
	75%B+25%R	356.25	1.39	-0.21
[56]	RCA1	355.8	1.40	-0.18
	RCA2	493.3	1.18	-0.13

Table 5. Ranges of k_1 and k_2 for untreated granular materials [42].

Author and Year	Material	k_1 (MPa)	k_2
Hicks (1970)	Partially crushed gravel, crushed rock	11-34.50	0.57-0.73
Hicks & Finn (1970)	Untreated base at San Diego Road Test	14.50-37.23	0.61
Allen (1973)	Gravel, Crushed stone	12.41-55.15	0.32-0.70
Kalcheff& Hicks (1973)	Crushed stone	27.60-62.00	0.46-0.64
Boyce et al. (1976)	Well graded crushed limestone	55.15	0.67
Monismith&Wictzak (1980)	In service base &subbase materials	20-53.43	0.46-0.65

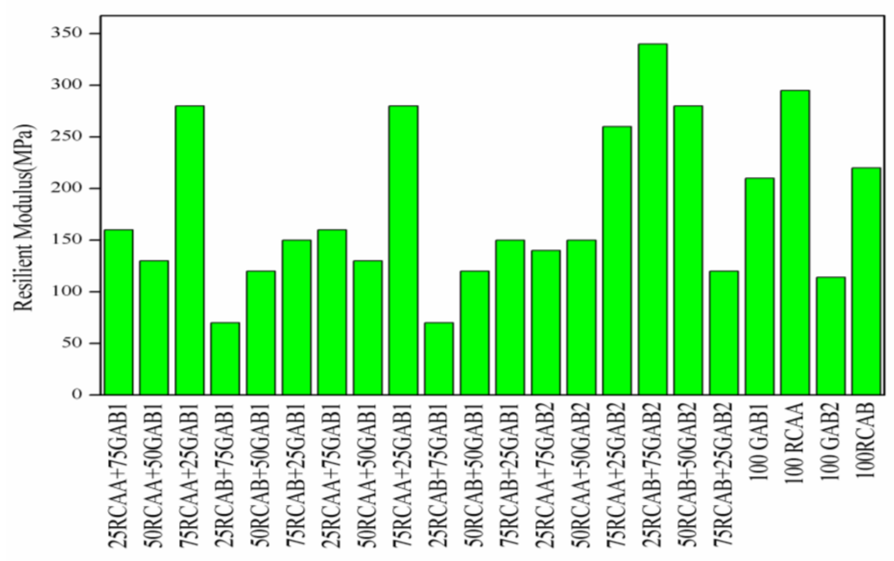


Fig. 5. Comparison of Resilient modulus for RCA and GAB mixes [47].

3. Studies on Stabilized RCA

The utilization of hydraulic binders to provide cohesion and improve stability on crushed stones cannot be considered the latest pavement construction technique [59]. The important factor for the successful use of crushed stones in paving is adequate compaction of the material. The compaction provides the material with a significant bearing capacity against vertical pressure. However, the material does not possess an excellent ability to take horizontal stresses even after it is compacted; the employment of binders can assist it by changing its original characteristics. Furthermore, to use recycled materials for special applications like pavement base or subbase, the improvement of recycled material is critical. Hence, several improvement techniques like stabilization with chemical additives and reinforcing with geo-grids are extensively used in pavement applications. The mechanistic-empirical pavement design considers stabilized materials under semirigid pavements (MEPDG 2008)[60]. Different stabilizers such as Portland cement, limes, pozzolans activated by lime, fly ash, ground slag, combinations of these, and geopolymers are used to stabilize RCA. Also, researchers have tested stabilized RCA by varying parameters such as stabilizer type and content. For the analysis of pavements with stabilized bases, MEPDG requires a resilient modulus and the modulus of rupture. These properties could be estimated from other tested properties like unconfined compressive strength through proper correlations.

3.1. Unconfined Compressive Strength of Stabilized RCA

The unconfined compressive strength (UCS) test is an extensively accepted method of testing to determine the strength of bound materials. UCS test gives the compressive strength of stabilized soil subjected to vertical compressive load. In addition, UCS is used to evaluate the quality of mix to perform satisfactorily as a stabilized base and sub-base layer [61]. Table 6 synthesizes the UCS test results reported in the literature to stabilize RCA with Ordinary Portland cement and alternative binders. Fig. 6, represents the average UCS variation of cement stabilized RCA with cement content ranging from 2 to 6 % by weight of RCA. Table 7 presents the criterion UCS for suitability of stabilized base and subbase.

3.2. Tensile Strength of Stabilized RCA

The tensile strength of stabilized aggregate is considered an important material parameter for pavement design. This is because the bottom of the stabilized layer undergoes tensile stress. Therefore, 3 point or 4 point flexural beam test and indirect tensile strength test have been used to determine the tensile strength of the stabilized base. Table 8 synthesizes tensile strength test results reported in the literature

3.3. Stiffness of RCA

Elastic modulus of stabilized materials is an important variable in layered elastic analysis to determine stresses and strains at critical locations i.e., at the bottom of the stabilized layer of a pavement. In general, the elastic modulus is computed at 10-40% of the strength of the mix, after a certain number of loading cycles have been applied, and is called resilient modulus. The standard methods used for determining resilient modulus include (1). Multi-stage repeated load triaxial test proposed by AASHTO T307-99[44] and (2). Dynamic indirect tension test offered by ASTM D 4123 [62] for stabilized pavement materials and (3). specimens subjected to repeated flexural loading by three-point or four-point flexure test. The stiffness or modulus values of stabilized materials depend on the type of test used in the laboratory. Table 9. presents the methods used to determine the stiffness of stabilized RCA by researchers. Table 10. provides the range of modulus for treated RCA.

The cyclic indirect diametrical tensile test is used to evaluate the tensile resilient modulus. The compression resilient modulus was determined using a repeated load triaxial setup using AASHTO T 307-99 protocol. A haversine load pulse of 0.1s loading and 0.9s rest period was applied. The flexural modulus was determined by repeated flexural four-point beam test.

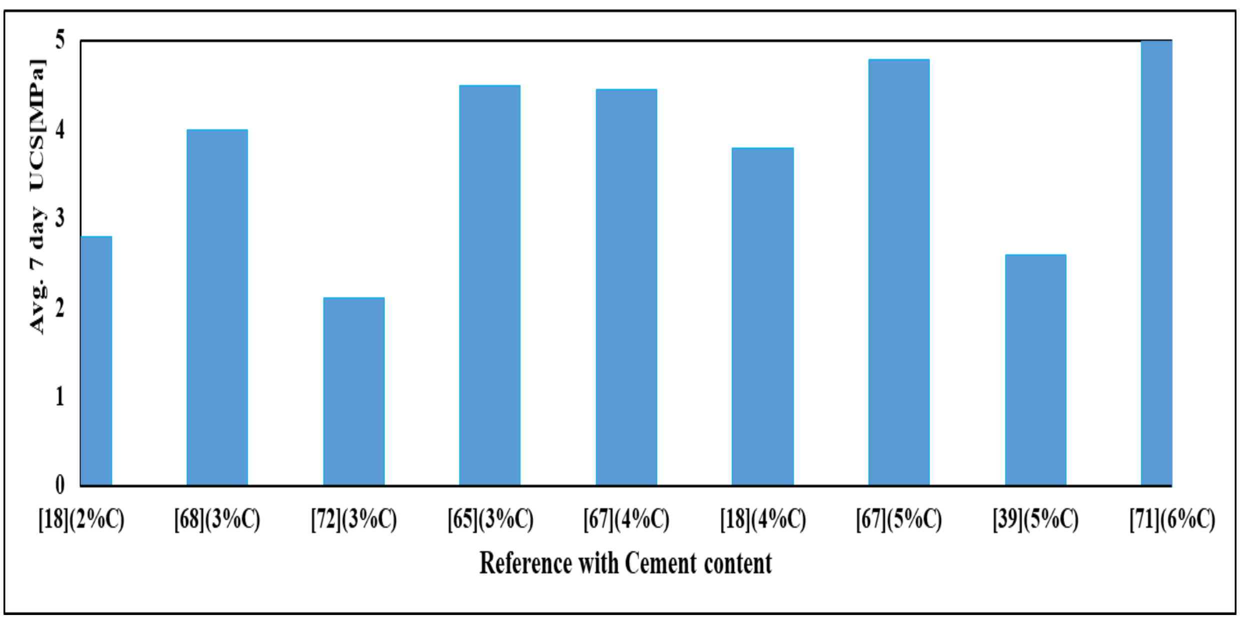


Fig. 6. UCS of cement stabilized RCA.

Table 6. Synthesis from the literature of the UCS values (MPa) of stabilized RCA.

Reference	Stabilizer	Test Protocol	UCS(MPa)	
			7-Day	28-Day
[63]	8.0%C	ASTM C 39[64]	-	6.22
	4.0 % C + 4.0%F		-	5.05
	8.0 % C + 8.0%F		-	13.63
	4.0% C+4.0%F+0.50%H		-	3.29
	8.0% C+8.0%F+0.50%H		-	10.72
[65]	3.0%C	Tex-120-E[66]	4.5	4.90
[67]	4.0% C	JTJ057-94	4.45	5.06
	5.0% C		4.79	5.38
[39]	5.0%C	ASTM C-39[64]	2.6	3.5
[68]	3.0%C	AS 5101.4-2008[69]	4.0	5.35
[18]	2.0% C		2.8	3.4
	4.0% C		3.8	4.2
[20]	2.0% F & 2.0% S at L/P ratio 0.3	ASTM D 5102[70]	1.80	3.20
	2.0% F & 2.0% S at L/P ratio 0.4		2.10	4.0
	2.0% F & 2.0% S at L/P ratio 0.5		1.80	3.60
	4.0% S at L/P ratio 0.3		2.20	4.20
	4.0% S at L/P ratio 0.4		2.70	4.70
	4.0% S at L/P ratio 0.5		2.50	4.40
[19]	10.0%CCR		1.08	-
	10.0%F		0.43	-
	10.0%S		6.30	-
	5.0%CCR+5.0%F		1.29	-
	5.0%CCR+5.0%S		3.37	-
	5.0%F+5.0%S		5.07	-
[21]	30.0%CKD		2.2	-
	20.0%CKD+10.0%F		3.8	-
	15.0%CKD+15.0%F		3.8	-
	10.0%CKD+20.0%F		2.8	-
	30.0%F		0.5	-
	20.0%LKD +10.0% F		1.2	1.4
[22]	30.0% CKD		2.0	2.2
	20.0% CKD +10.0% F		3.0	3.5
	15.0% CKD +15.0%F		3.2	.8
	10.0%CKD +20.0%F		2.8	3.2
	30.0%F		0.4	1.0
[71]	6.0% C	JTG E51-2009 T080501994	5.6	-
	6.0%C + 1.6% E		5.0	-
	6.0%C +0.9% O		5.8	-
[72]	3.0% C	ASTM D 5102[70]	2.11	-
	3.0%C + 0.5% PVA		0.69	-
	3.0%C + 1.0% PVA		0.94	-
	3.0%C + 1.5% PVA		2.28	-
	3.0%C + 2.0% PVA		3.74	-

C-Cement; CCR-Calcium Carbide Residue; CKD-Cement Kiln Dust; E- Slow setting cationic emulsion; F-Fly ash (Class-F); H- High-density polyethylene fibers; LKD- Lime Kiln Dust; L/P-Liquid activator to solid pozzolanic material; O-Waste Oil; PVA-Poly Vinyl Alcohol; S- Ground granulated blast furnace slag;

Table 7. Criteria for UCS suitability of stabilized base and sub-base.

Reference	Unconfined Compressive Strength (Mpa)				Curing Period
	High Volume Roads		Low Volume Roads		
MEPDG (2008)[60]	1.72	Subbase	1.72	Subbase	7-Day for cement 28-Day lime -fly ash
	5.1	Base	5.17	Base	
AUSTROADS(2008)[73]	2.0		1-2		28-Day Curing
IRC:37-2018[74]	0.75-1.5	Subbase	1.7	Subbase	7-Day for cement 28-Day lime-fly ash
	4.5-7.0	Base	3.0	Base	

Table 8. Synthesis from the literature of the tensile strength values of stabilized RCA.

Reference	Blend of Materials	Test Protocol	Tensile Strength [MPa]
[63]	8.0%C	ASTM C 496[75]	0.65
	4.0%C + 4.0%F		0.77
	8.0%C + 8.0%F		1.56
	4.0%C+4.0%F+0.50%H		0.96
	8.0%C+8.0%F+0.50%H		1.44
	4.0%C + 4.0%F	ASTM C 78[76]	0.94
	8.0%C + 8.0%F		0.91
	4.0%C+4.0%F+0.50%H		1.06
	8.0%C+8.0%F+0.50%H		1.44
[39]	5.0%C+25.0%LSA	ASTM C-78[76]	0.41
		ASTM C496[75]	0.32
[68]	3.0%C	AS1012.11-2000[77]	1.23
[78]	10.0%CCR		0.09
	10.0%F		-
	10.0%S		1.90
	5.0%CCR+5.0%F		0.91
	5.0%CCR+5.0%S		1.83
	5.0%F+5.0%S		2.10
[79]	3.0%C		0.88
	3.0%C+5.0%PET		0.30

Table 9. Methods used for Stiffness Evaluation.

Reference	Type of stabilizer	Test Procedure	Curing Period (Days)	Test Protocol
[18]	Cement	AASHTOT307-99[44]	7.0	Tex-120-E[66]
[20]	F and S Geo-polymer		7.0	
[19]	CCR, F andSGeo-polymer		7.0	
[21]	CKD, F Geo-polymer		7.0	[51]
[22]	F and CKD		7.0	
[78]	Alkali activated CCR	[80]	28.0	
[71]	C, E and O	-	90.0	JTGE51-2009T0808-1994
[79]	C and PET	[80]	28.0	
[72]	C and PVA	[44]	7.0	[51]

Table 10. Range of Resilient Modulus for RCA stabilized with different binders.

Compression Resilient Modulus			Tensile or Flexural Resilient Modulus		
Reference	Material	M_R (MPa)	Reference	Material	M_R (MPa)
[19]	RCA	255 - 693	[63]	4.0%C+4.0%F	690
	RCA+10.0%CCR	75 - 330		8.0%C+8.0%F	790
	RCA +10.0%F	108 - 250		4.0%C+4.0%F+0.50% H	1,090
	RCA +10.0%S	384 - 776		8.0%C+8.0%F+0.50% H	690
	5.0%CCR+5.0%F	203 - 516	[78]	10.0%S	12,455
	5.0%CCR+5.0%S	373 - 852		5.0%CCR+5.0%F	8,288
	5.0%S+5.0%F	130 - 402		5.0%CCR+5.0%S	10,187
[21]	30.0% LKD	360		5.0%F+5.0%S	11,889
	20.0%LKD+10%F	350	[79]	3.0% C	7,815
	15.0%LKD+15.0 %F	340		3.0% C + 5.0% PET	4,985
	10.0%LKD+20.0 %F	250	[71]	5.0% C	1,702
	30.0%F	300		5.0%C +E	1,270
				5.0%C + 0.9 O	1,428

4. Recycled Concrete Aggregates Stabilized with Geo-Synthetics

Geosynthetics such as geogrids, geotextiles, are popularly used in construction activities for soil reinforcement. The geogrid is most commonly used in the base or subbase layers of flexible pavement. This is because geogrid has large aperture size where soil particles can interlock easily from one side to another side and thereby enhance strength and stiffness of the pavement layer [81].

Liu et al.[82] executed finite element analysis using stress intensity factor distribution on asphalt concrete pavements with geo-grid reinforced RCA and natural aggregate bases. They concluded that geo-grid decreased crack propagation rate into the top layer of pavement and reinforced RCA performed better than crushed natural aggregate. Gongora & Palmira [83] undertook a laboratory cyclic plate loading test on unreinforced and biaxial geo-grid reinforcement sections constructed inside a steel tank of 750mm diameter and 530mm height. New aggregate and RCA were used as base materials. The geogrid was placed at the subgrade interface and at the base in the case of reinforced section. The deformations measured at several locations indicated that geo-grid enhanced the life of RCA base.

Arulrajah et al. and others [55,84] investigated interface shear strength, $M_{R,}$ and permanent deformation properties of geogrid reinforced RCA using conventional(C) and modified(M) large-scale direct shear test apparatus. Table 11 presents interface shear strength properties and Table 12 presents permanent strain for RCA as well as geogrid RCA. The study concluded that permanent deformation properties of geo-grid reinforced RCA improved compared to unreinforced material. Walkenbach et al.[85] reported that the NA replacement with RCA and triaxial geogrid increased resilient deformation. The interface stress was found to be reduced by 55%, representing greater stress distribution.

Table 11. Interface peak shear strength properties of geogrid reinforced RCA [55].

Material	Apparent cohesion				Interface angle			
	Peak		Residual		Peak		Residual	
	C	M	C	M	C	M	C	M
RCA	95	-	80	-	65	-	39	-
RCA+Biaxial	75	108	25	10	50	69	39	67
RCA+Triaxial	83	114	50	12.5	52	71	35	68

Table. 12 Permanent strain(micro) of geogrid reinforced RCA [84].

Deviator stress(kPa)	150	250	350
RCA	11742.3	16077.8	Failed
RCA+Biaxial	8293.4	15994.4	Failed
RCA+Triaxial	7478.6	15070.1	Failed

5. Pavement performance with RCA as a base material

Barksdale et al. [86], investigated recycled concrete base materials by RLTT to evaluate resilient modulus and rutting potential. The study reported that recycled concrete materials performed better compared to crushed gravel for rutting potential. The granular equivalency of RCA was estimated based on rutting potential and resilient modulus. There was considerable variation in RCA performance compared to that of other base materials. Cavey et al. [87] conducted laboratory and field studies to assess the potential suitability of pavement base course material containing reinforced cement stabilized RCA with reclaimed plastic strips. The field program constructed 12 test sections, and it was found that the addition of fibers did not affect field compaction. Laboratory tests showed better performance in terms of split tensile strength and beam flexural strength. The results suggested that caution and careful investigation should be exercised at the time of incorporation of waste products into component layers.

Chini et al.[88] evaluated the effect of RCA as a base material on the performance of hot mix asphalt (HMA). A circular accelerated test track was constructed with 200, 250, and 300mm base course thickness. A 90mm thick layer of HMA was laid over each base course. The life of flexible pavement was then estimated and stated that the properties of RCA was found to be consistent. Ho et al. [89] reported a field study where RCA was used as a base course material. The International Roughness Index (IRI) was found to vary between 1-4 m/km. The rut depth was found more in the case of pavement with RCA base course. Jimnez et al. [38] determined RCA's performance and environmental impact on unpaved road surfaces. The IRI measured values were similar to those of the pavement constructed with NA and both roads were in good condition vis-a-vis unpaved rural roads (between 2.5m/km to 6.0m/km). However, after 2.5 years, the evaluation studies showed that IRI for the pavement with NA increased about 100%, whereas RCA increased slightly by 35%. Coban et al. [90] evaluated the use of RCA and recycled asphalt pavement (RAP) material in pavement foundation systems as a substitute to NA. Four pavement sections with base layers of thickness 300mm consisting of coarse RCA, fine RCA, and limestone (control), the combination of RCA with RAP materials were constructed for Minnesota Road Research Project Low Volume Road (Mn ROAD LVR) test facility. The modulus of base layers and the materials were evaluated using falling weight deflectometer and laboratory resilient modulus test. The results exhibited that coarse RCA and fine RCA produced higher elastic modulus compared to RCA with RAP.

6. Summary and Concluding Remarks

This paper summarizes the state of research on the utilization of RCA in base layers of pavement structures. Based on review of several researchers' investigations, RCA has great potential for use in pavement base applications. The following conclusions were drawn:

- RCA is a competent alternative material to NA to provide a stable and durable pavement base.
- The use of RCA increases the OMC for compaction procedures adopted in pavement construction. The CBR of RCA is comparable to that of NA.
- The base made with RCA exhibited a higher resilient modulus and lower accumulated permanent deformation than NA. A combination of NA and RCA results in reduced modulus which may be due to poor packing of materials.
- The studies considered the effect of only moisture on determination of M_R.

- The constitutive models for M_R presented in the literature were derived for subgrade soils and virgin aggregates, although, the use of such models could result in uncertainties. Therefore, the equations should be further validated, and this can be accomplished by applying RCA for case studies.
- Minimal information is available on fatigue behavior of several composites used to stabilize RCA.
- The use of stabilized RCA has been limited to experiments.

7. Further scope of research

The review on RCA as a pavement base material indicated certain knowledge gaps on which further research is required to use RCA as an alternative to NA for pavement applications. These are:

1. The effect of mortar content on performance of RCA based pavement base need to be studied.
2. The effect of gradation must be taken into account for evaluation of stiffness and permanent deformation for RCA based pavement base.
3. Properties such as moisture susceptibility, durability, leaching, and shrinkage of stabilized RCA should be considered in the performance evaluation.
4. Field performance of pavements with RCA and stabilized RCA should be evaluated.
5. The economic analysis of pavements containing RCA should be carried out.

References

[1]. Mani M, Venkatarama Reddy BV. (2012).Sustainability in human settlements: imminent materials and energy challenges for buildings in India." Journal of the Indian Institute of Science, 92, 145-162.

[2]. Jain S, Singhal S, Jain NK.(2018). Construction and demolition waste (C&DW) in India: generation rate and implications of C&DW recycling. Int J of Constr Manag. 21:3, 261-270. doi.org/10.1080/15623599.2018.1523300

[3]. Akhtar A, and Sarmah. (2018). Construction and demolition waste generation and properties of recycled aggregate concrete: A global perspective. J. Clean. Prod, Vol. 186, 262-281. doi.org/10.1016/j.jclepro.2018.03.085.

[4]. Kazemian F, Rooholamini H, Hassani A. (2019). Mechanical and fracture properties of concrete containing treated and untreated recycled concrete aggregates. Constr. Build. Mater. Vol. 209, P. 690-700. doi.org/10.1016/j.conbuildmat.2019.03.179 .

[5]. Maria AD, Eyckmans J, Acker KV. (2018). Downcycling versus recycling of construction and demolition waste: Combining LCA and LCC support sustainable policy making. Waste Manage. Vol. 75, P.3-21. doi.org/10.1016/j.wasman.2018.01.028.

[6]. Limbachiya MC, Koulouis A, Roberts JJ, Fried AN.(2004). Performance of recycled aggregate concrete. Proc. RILEM International Symposium on Environment-Conscious Materials and Systems for Sustainable Development, 2004, Koriyama, Japan, 127-136.

[7]. Islam R, Nazifa TH, Yuniarto A, Uddin ASMS, Salmiati S, Shahid S. (2019). An empirical study of construction and demolition waste generation and implication of recycling. Waste Manage. doi.org/10.1016/j.wasman.2019.05.049.

[8]. O Mahony MM, Milligan GWE. (1991). Use of recycled materials in subbase layers. Transport Res. Record 1991; 1310: 73-80.

[9]. Bennert T, Papp WJ, Maher A, Gucunski N. (2000). Utilization of construction and demolition debris under traffic type loading in base and subbase applications. J. Transportation Research Record, 1714, 33-39.

[10]. Park T. (2003). Application of Construction and Building Debris as Base and Subbase Materials in Rigid Pavement. J Transp Eng-ASCE 2002; 129(5): 558-563. doi.org/10.1061/(ASCE)0733-947X(2003)129:5(558).

[11]. Poon CS, Chan D.(2006). Feasible use of recycled concrete aggregates and crushed clay brick as unbound road subbase." Constr. Build. Mater., Vol.20, P.578-585. doi.org/10.1016/j.conbuildmat.2005.01.045.

[12]. Blankenagel BJ, Guthrie W.S. (2006). Laboratory characterization of recycled concrete for use as pavement base material. Transport. Res. Rec., No. 1952, Washington, D.C., 2006, 21-27.

[13]. Arulrajah A, Piratheepan J, Ali MMY, Bo MW.(2012). Geotechnical properties of recycled concrete aggregate in pavement subbase applications." Geotec. Test. J., 35(5), 1-9.

[14]. Arulrajah A, Disfani MM, Horpibulsuk S, Suksiripattanapong C, Prongmanee N. (2014a).Physical properties and shear strength responses of recycled construction and demolition materials in unbound pavement base/subbase applications. Constr. Build. Mater. doi.org/10.1016/j.conbuildmat.2014.02.025.

[15]. Arisha AM, Gabr AR, El-Badawy SM, Shwally SA.(2018).Performance evaluation of construction and demolition waste materials for pavement construction in Egypt." J. Mater. Civil. Eng. doi.org/10.1061/(ASCE)MT.1943-5533.0002127.

[16]. Ardalan N, Wilson DJ, Larkin TJ.(2020). Analyzing the Application of Different Sources of Recycled Concrete Aggregate for Road Construction. Transp. Res. Rec. J. Transp. Res. Board 2020.

[17]. Puppala AJ, Wattanasantichareon E, Hoyos LR.(2003).Ranking of four chemical and mechanical stabilization methods to treat low volume road subgrade in Texas. Transportation Research Record1819, Transportation Research Board, Washington, DC, pp.63-71.

[18]. Mohammadinia A, ArulrajahA, Sanjayan J, Disfani MM, Bo MW, Darmawan S. (2014).Laboratory evaluation of the use of cement-treated construction and demolition materials in pavement base and subbase applications. J. Mater. Civ. Eng. doi.org/10.1061/(ASCE)MT.1943-5533.0001148

[19]. Arulrajah A, Mohammadinia A, Phummiphan I, Horpibulsuk S, Samingthong W.(2016). Stabilization of recycled demolition aggregates by geopolymers comprising calcium carbide, fly ash and slag precursors. Constr. Build. Mater., 114, 864-873. doi.org/10.1016/j.conbuildmat.2016.03.150

[20]. Mohammadinia A, Arulrajah A, Sanjayan J, Disfani MM, Win Bo M, Dharmawan S. (2016).Stabilization of demolition materials for pavement base/subbase applications using fly ash and slag geopolymers: laboratory investigations.J. Mater. Civ. Eng., doi.org/10.1061/(ASCE)MT.1943-5533.0001526.

[21]. Arulrajah A, Mohammadinia A, D'Amico, Horpibulsuk S.(2017). Cement kiln dust and fly ash blends as an alternative binder for the stabilization of demolition aggregates.Constr. Build. Mater. 145, 218-225. doi.org/10.1016/j.conbuildmat.2017.04.007.

[22]. Mohammadinia A, Arulrajah A, D Amicao, Horpibulsuk S. (2018). Alkali activation of fly ash and cement kiln dust mixtures for

stabilization of demolition aggregates.Constr. Build. Mater. 186: 71-78.doi.org/10.1016/j.conbuildmat.2018.07.103.

[23]. Giri JP, Panda M, Sahoo UC.(2018a). Performance Of Bituminous Mixes Containing Emulsion Treated Recycled Concrete Aggregates. J. Mater.Civ. Eng. doi.org/10.1061/(ASCE)MT.1943-5533.0002239

[24]. Maduabuchukwu Nwakaire C, Poh Yap S, Chuen Onn C, Wah Yuen C, AdebayoIbrahim H.(2020). Utilization of recycled concrete aggregates for sustainable highway pavement applications; a review. Construct. Build. Mater.doi.org/10.1016/j.conbuildmat.2019.117444.

[25]. Sanger M, Natarajan BM, Wang B, Edil T, Vogel MG.(2020). Recycled concrete aggregate in base course applications: Review of field and laboratory investigations of leachate pH. J. Hazard. Mater.doi.org/10.1016/j.jhazmat.2019.121562.

[26]. Aytekin B, Aghabaglou AM. (2022). Sustainable materials: A review of recycled concrete aggregate utilization as pavement material. Transportation Research Record. doi.org/10.1177/03611981211052026 .

[27]. Akbarnezhad A, Ong KCG, Zhang MH, Tam CT.Acid treatment technique for determining the mortar content of recycled concrete aggregates. J. ASTM Int., Vol.41, 2013, pp.441-450.

[28]. Gabr AR, Cameron DA.(2012). Properties of recycled concrete aggregate for unbound pavement construction. J. Mater. Civ. Eng., doi.org/10.1061/(ASCE)MT.1943-5533.0000447.

[29]. Edil B. (2017).A review of recycled aggregates (RAP and RCA) as unbound base course material for sustainable highway construction. Proceedings of the 4th congress International de Geotechnique-Ouvrages-Structures, Springer.

[30]. Tam VWY, Tam CM.(2007).Crushed aggregate production from centralizing combined and individual waste sources in Hong Kong. Construct. Build. Mater. doi.org/10.1016/j.conbuildmat.2005.12.016.

[31]. Arulrajah A, Ali M, Disfani M, Horpibusuk S.(2014a).Recycled glass blends in pavement base/subbase applications: laboratory and field evaluation. J. Mater. Civil. Eng. doi.org/10.1061/(ASCE)MT.1943-5533.0000966

[32]. Cooley LA, Hornsby H. (2012). Evaluation of Crushed Concrete Base Strength. Report, Mississippi Department of Transportation, Jackson, MS.

[33]. Bennert T, Maher A.(2005).The development of a performance specification for granular base and subbase material.Report No. FHWA-NJ-2005-003.

[34]. Poon CS, Chan DX.(2006b). Feasible use of recycled concrete aggregates and crushed clay brick as unbound road subbase. Construct. Build. Mater.20(8), 578-585.

[35]. Poon CS, Chan D.(2006a). The use of recycled aggregate in concrete in Hong-Kong. Resour. Conserve. Recycl.

[36]. Bennert T, Maher A. (2008). The use of recycled concrete aggregate in a dense graded aggregate base course. U. S. Department of Transportation, FHWA, New Jersey Department of Transportation, New Jersey, USA, p.65.

[37]. Melbouci B. (2009). Compaction and shearing behavior study of recycled aggregates. Constr. Build. Mater. 23(8), 2723-2730.

[38]. Jimnez JR, Ayuso J, Argela F, Lopez, M, Galvin, AP.(2012).Utilization of unbound recycled aggregates from selected CDW in unpaved rural roads. Resour., Conserv. Recycle. 58. 88-97. doi.org/10.1016/j.resconrec.2011.10.012

[39]. Behiry AE.(2013). Utilization of cement treated recycled concrete aggregates as

base or subbase layer in Egypt. Ain Shams Engineering Journal, pp661-673. doi.org/10.1016/j.asej.2013.02.005.

[40]. Haider I, Cetin B, Kaya Z, Hatipogulu M, Cetin A, Ahmet HA.(2014). Evaluation of the mechanical performance of recycled concrete aggregates used in highway base layers. Geo-Congress 2014 Technical papers at Geo-Characterization and Modeling for Sustainability, ASCE, Reston, VA, 3686-3694.

[41]. Echevarria MJM, Alonso ML, Garach L, Alegre J, Poon CS, Agrela F, Cabrera M.(2020).Crushing treatment on recycled aggregates to improve their mechanical behavior for use in unbound road layers.Constr. Build. Mater. 263 (2020) 120517

[42]. Huang, Y. H. (1993). *Pavement analysis and design*, Prentice-Hall, Englewood Cliffs, N.J.

[43]. American Association of State Highway and Transportation Officials.Standard Test Method for Determining the Resilient Modulus of Soils and Aggregate Materials. (AASHTO TP46-94). Washington, D. C.

[44]. American Association of State Highway and Transportation Officials. Standard method of test for determining the resilient modulus of soil and aggregate materials.AASHTO T 307-99 (2007)

[45]. NCHRP (2000), Harmonized test methods for laboratory determination of resilient modulus for flexible pavement design, Volume 1: Unbound granular material. NCHRP Project 1-28a Draft Report, 198p.

[46]. Lekarp F, Isacsson U, Dawson A. (2000). State of the art II-Permanent strain response of unbound aggregates. J. Transp. Eng., 76-83.

[47]. Aydilek AH. (2015). Environmental Suitability of Recycled Concrete Aggregates in Highways. Research report, Maryland State Highway Administration.

[48]. Nataatmadja A, Tan YL. (2001). Resilient response of recycled concrete road aggregates. J. Transp. Eng., 127(5), 451-453.

[49]. Molin C, Larsson K, Arvidsson H. (2004).Quality of reused crushed concrete strength, contamination, and crushing technique. International RILEM conference on the use of recycled materials in buildings and structures. RILEM Publications, Barcelona, Spain, pp150-155.

[50]. Jitsangiam P, Nikraz H, Siripun K.(2009). Construction and demolition (C&D) waste as a road base material for Western Australia roads. Aust. Geomech. J., 44(3), 57-62.

[51]. Vuong BT, Brimble R(2000). Austroads repeated load triaxial method-Determination of permanent deformation and resilient modulus characteristics of unbound granular materials under drained conditions. APRG Document 00/33 (MA), Melbourne, Australia.

[52]. Bozyurt O, Tinjum JM, Son YH, Edil T. B, Benson CH.(2012). Resilient modulus of recycled asphalt pavement and recycled concrete aggregate. GeoCongress 2012, 3901-3910.

[53]. Azam AM, Cameron DA, Rahman MM. (2013). Model for prediction of resilient modulus incorporating matric suction for recycled unbound granular materials. Can. Geotech. J., 50(11), 1143-1158. doi.org/10.1139/cgj-2012-040

[54]. Applied Research Associates (ARA). (2004). Guide for mechanistic-empirical design of new and rehabilitated pavement structures. Final Rep., National Cooperative Highway Research Program (NCHRP) Project1-37A, Albuquerque, NM.

[55]. Arulrajah A, Rahman MA, Piratheepan J, Bo MW, Imteaz MA.(2014). Evaluation of interface shear strength properties of geogrid-reinforced construction and demolition materials using a modified large scale direct shear testing apparatus. Journal of Materials in Civil Engineering. 26 (5), 974–982.

[56]. Bestgen JO, Hatipogulu M, Cetin B, Aydilek AH. (2016). Mechanical and environmental suitability of recycled concrete aggregate as a highway base material. J. Mater. Civ. Eng., doi.org/10.1061/(ASCE)MT.1943-5533.0001564

[57]. Jayakody S, Gallage C, Ramanujam J. (2019). Performance characteristics of recycled concrete aggregate as an unbound pavement material. Heliyon 5 (9):doi.org/10.1016/j.heliyon.2019.e02494.

[58]. Gabr AR, Mills KG, Cameron DA. (2013). Repeated load triaxial testing of recycled concrete aggregate for pavement base construction. Geotech. Geol. Eng., doi.org/10.1007/s10706-012-9572-8

[59]. Balbo JT. (1997). High-quality cement treated crushed stones for concrete pavement bases. 6th Purdue Conference on Concrete Pavement. Proc., 6th Int. Conf. on Concrete Pavement Design and Materials for High Performance, International Society for Concrete Pavements, Indianapolis.

[60]. MEPDG. Guide for Mechanistic-Empirical Pavement Design Guide. AASHTO, 2008.

[61]. Yeo YS, Jitsangiam P, Nikraz H. (2011). Mix design of cementitious base course. International conference on advances in Geotechnical Engineering, pp. 379-385(2011).

[62]. ASTM (1995). Standard test method for indirect tension test for resilient modulus of bituminous mixtures. ASTM D-4123.

[63]. Sobhan K, Mashnad M. (2000). Fatigue durability of stabilized recycled aggregate base course containing fly ash and waste - plastic strip reinforcement. Final Rep. Submitted to the Recycled Materials Resource Centre, Univ. of New Hampshire, Dept. of Civil and Geological Engineering, New Mexico State Univ., Las Cruces, NM.

[64]. ASTM. (2014). Standard test method for compressive strength of cylindrical concrete specimens. ASTM C39/C39M-14.

[65]. Guthrie WS, Sebesta S, Scullion T. (2002). Selecting optimum cement contents for stabilizing aggregate base materials. Technical report for the Texas Department of Transportation; 53p.

[66]. Texas Dept. of Transportation (TxDOT).(2013). Test procedure for soil-cement testing. Tex-120-E, Austin, TX.

[67]. Li Y, Sun X, Yin J. (2010). Mix design of cement stabilized aggregate base course material. Geo-Shanghai 2010 International Conference, Paving Materials and Pavement Analysis, ASCE, 184-192.

[68]. Disfani MM, Arulrajah A, Hahhighi H, Mohammadinia A, Horpibulsuk S. (2014). Flexural beam fatigue strength evaluation of crushed brick as supplementary material in cement stabilized recycled concrete aggregates. Constr. Build. Mater., 68, 667-676.

[69]. AS 5101.4-2008. Methods for preparation and testing stabilized materials unconfined compressive strength of compacted materials. Standards Australia

[70]. ASTM. (2009). Standard test method for unconfined compressive strength of compacted soil lime mixtures. ASTM D 5102-09.

[71]. Zhou J, Zeng M, Chen Y, Zhong M. (2019). Evaluation of cement stabilized recycled concrete aggregate treated with waste oil and asphalt emulsion. Constr. Build. Mater. 199(Feb): 143-153.

[72]. Yaowarat T, Horpibulsuk S, Arulrajah A, Maghool F, Mirzababei M, Rashid A, Chinkulkijniwat. (2020).Cement stabilization of recycled concrete aggregate modified with polyvinyl alcohol. Int. Jour. Pav. Eng., pp 1-9.

[73]. AUSTROADS (2008). Guide to pavement technology: Pavement Structural Design.

[74]. IRC (Indian Roads Congress).2018. Guidelines for the design of flexible pavements. Indian code of practice. IRC:37. New Delhi, India.

[75]. ASTM. (1996). Standard test method for splitting tensile strength of cylindrical concrete specimens. ASTM C496-96.

[76]. ASTM. (2009). Standard test method for flexural strength of concrete (Using simple beam with third point loading). ASTM C78-09.

[77]. AS1012.11-2000. Methods of testing concrete, Method 11: Determination of the modulus of rupture. Standards Australia 2000.

[78]. Mohammadinia A, Arulrajah A, Phummiphan I, Horpibulsuk S, Mirzababei M. (2019). Flexural fatigue strength of demolition aggregates stabilized with alkali-activated calcium carbide residue. Constr. Build. Mater. 199 (Feb): 115-123.

[79]. Arulrajah A, Perera S, Wong YC, Horpibulsuk S, Maghool F. (2020). Stiffness and flexural strength evaluation of cement stabilized PET blends with demolition wastes. Constr. Build. Mater.

[80]. Austroads,APT101/08. The development and evaluation of protocols for the laboratory characterization of cemented materials.

[81]. Rahman MA, Arulrajah A, Piratheepan J, Bo MW, Imteaz MA. (2014a). Resilient modulus and permanent deformation responses of geogrid reinforced construction and demolition materials. J. Mater. Civ. Eng., 512-519.

[82]. Liu X, Scarpas A, Blaauwendraad J, Genske DD. (1998). Geogrid reinforcing of recycled aggregate materials for road construction: Finite element investigation.Transportation Research Record, 1611, 78-85.

[83]. Gongora I AG, Palmira EM. (2012). Influence of fill and geogrid characteristics on the performance of unpaved roads on weak subgrades. Geosynthetics International, 19(2), 191-199.

[84]. Rahman MA, Arulrajah A, Piratheepan J, Bo MW, Imteaz MA. (2014d). Resilient modulus and permanent deformation responses of geogrid reinforced construction and demolition materials. J. Mater. Civ. Eng, 26 (3), 512-519.

[85]. Walkenbach T N, Han J, Parsons RL, Li Z. (2020). Effect of Geogrid Stabilization on Performance of Granular Base Course over Weak Subgrade. In Geo-Congress 2020: Geotechnical Earthquake Engineering and Special Topics (pp. 527-535): ASCE Reston, VA.

[86]. Barksdale RD, Itani SY, Swor TE.(1992). Evaluation of recycled concrete, open-graded aggregate, and large top size aggregate bases. Transportation Research Record *1345*, TRB, National Research Council, Washington, D.C., 92-100.

[87]. Cavey JK, Krizek RJ, Sobhan K, Baker WH.(1995). Waste fibers in cement stabilized recycled aggregate base course material. Proc., Environmental Testing and Evaluation of Stabilized Wastes, Performance of Stabilized Materials, and New Aggregate Tests, Transportation Research Record 1486, National Research Council, Washington, D.C. 97-106.

[88]. Chini AR, Kuo S, Armaghani JM, Duxbury JP. (2001). Test of recycled concrete aggregate in accelerated test track. J. Transp. Eng., 127(6). 486-492.

[89]. Ho NY, Lee YPK, Tan JY.(2008). Beneficial use of recycled concrete aggregate for road construction in Singapore. 6th International Conference on Road and Airfield Pavement Technology, Sapporo, Japan p.8

[90]. Coban HS, Cetin B, Ceylan H, Edil T, Nazarian S. (2020). Evaluation of field and laboratory stiffness of recycled materials used in pavement base layers.Geo-Congress, ASCE, 318pp 582-590.