Strength Assessment of Recycled Construction & Demolition Waste in Pavements

Piyush K. Bhandari
Department of Civil Engineering
Dr. Vithalrao Vikhe Patil College of Engineering, Ahmednagar, M.S., India

Abstract— Current pace of construction put behind huge amount of construction waste. Even old structures are removed while lead to demolition waste. These wastes are not handled as per municipal guidelines and treated in illegal way. The Construction and demolition waste may affect environment and social issues related to public health and economy. This waste can be a possible alternative for aggregates in pavement construction. Main aim is to acquire data regarding quality and quantity of waste and study proper management policies regarding handling this waste. Present investigation studied the geotechnical and structural properties of waste material and its suitability as construction material. Based on test results the composition of demolition waste, its source will affect the strength of prepared recycled aggregate. Even the compactive effort applied to stabilize the material will affect the strength values of California bearing ratio and Plate load test results. Test results revealed recycled construction and demolition waste (RCDW) as a suitable material for base and sub-base construction in pavement construction.

Keywords: Construction and demolition waste, pavement, recycling, compactive effort, deformation

I. Introduction

Large amount of construction and demolition waste goes untreated and is dumped directly to landfill sites. In 2018, within India 21,000 tons of demolition was handled within a year. It accounted 57% of total solid waste in that year. Amongst that only 25% waste was handled by adapting standard procedure and dumped to landfill, whereas remaining waste may found its way to unauthorized dumping on public lands and even in water bodies. Thus it may cause pollution of land as well as water. There are two methods to determine amount of construction and demolition (C&D) waste. First method is measuring amount of waste entering landfill site and second method directly considers 10% of total construction material utilized for new construction as source of waste [1]. Disposal of this waste is expensive and labour intensive work [2]. In past, research has confirmed huge potential of demolition waste to be used as construction material either directly or by processing. This recycled construction and demolition waste (RCDW) is promising alternative to replace aggregate in road construction [3, 4-17]. It has performed well as base and sub-base material on road construction. Only main hindrance for its regular use is variation in its grade and quality [18]. There is a need to develop standard guidelines which could provide design strength and quality values for use of RCDW as aggregate during pavement construction. In present paper, extensive work was performed to assess quality of available recycled waste material which is alternative for base and sub-base material. Further laboratory investigation was performed to supplement the strength assessment of material provided. Physical and mechanical properties of material were evaluated and compared with standard ingredients of pavement construction. Final conclusion was drawn based upon results for water absorption test, California bearing ratio (CBR) test, plate load test to decide usefulness of RCDW in pavement construction.

There has been tremendous increase in volume of Municipal solid waste (MSW) in India. It is assumed that Construction & Demolition (C&D) waste is 25 to 30% of total MSW. Fig. 1 gives projected MSW volume on forthcoming years [19]. China has similar issue regarding handling construction waste. It has 40% of total MSW as C&D waste which is approximately 200 million tons [20, 21]. In India there is lack of efficient waste management system and people are unaware about serious consequences due to rising of C& D waste and shortfall of dumping sites [22]. Municipal bodies need to work of efficient methodologies to handle this waste. Demolition waste basically consists of agglomerate of concrete, mortar, steel, wood, plastic, ceramic, clay bricks, etc [23, 24]. Fig. 2 gives percentage distribution of different constituents of C&D waste in India in 2018 [25]. In Different metropolis of India, state and local municipal bodies are striving hard to install sufficient capacity C& D waste handling plants. But the efforts required to handle such huge quantity waste are falling short. Problems associated while handling C& D waste are lack of funds, lack of strategy, lack of training, lack of skilled labour, No plan for recycling , No laws, No public support and lack of government initiatives [26, 27, 28]. Table 1 gives discrepancy of Recycling plants in handling C&D waste.

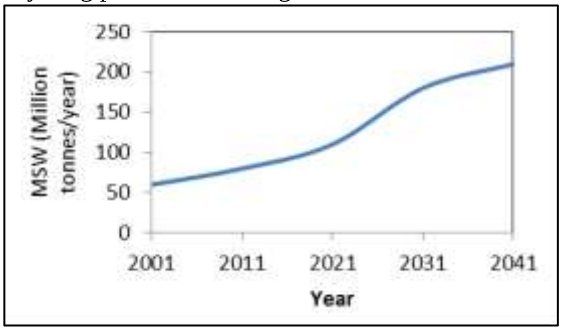


Fig. 1: MSW waste in decades in India

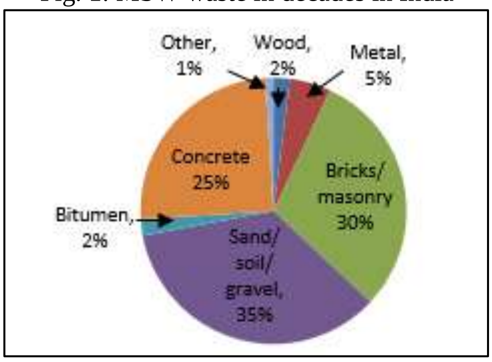


Fig. 2: Percentage Distribution of C&D waste

Construction waste is not collected in systematic manner. In fact waste must be segregated at collection point itself. Often it is dumped at illegal dumping sites [29, 30]. Different alternatives were investigated and best possible option to use C&D waste in road construction activity was proposed after careful handling and separation of C& D waste from other MSW.

Construction waste consists of bricks, tiles, wood, plastic etc. These materials are properly segregated to separate concrete, mortar and bricks bats from remaining material. Electrical fragmentation technology has successfully been used to segregate construction waste and supply raw material to new construction sites [31]. C&D waste obtained is feed to jaw crushers to grind them to required shape and size. Well planned process consisting of segregation, grinding, size reduction and sieving is followed to get well graded recycled aggregates. In present investigation RCDW was derived from construction and demolition sites within Ahmednagar province. Both materials were collected and feed to local stone crusher to obtain recycled aggregates. Approximately 0.5 tones of RCDW collected from different sites. Proper record was maintained to know the source of waste. Regular batching was done to get consistent recycled aggregates during different stage of research work. Prepared sample was procured in test laboratory and evaluated to determine physical and mechanical properties before subjected to testing activity.

Sr. No.	Cities	C & D waste generation (Million tons)	Estimated capacity of recycling plants (Million tons)	Discrepancy
1	Delhi	7000	4150	40.7%
2	Ahmedabad	700	1000	42.8 % Surplus
3	Kolkata	1600	NA	100% (No facility)
4	Mumbai	2500	1200	52%
5	Pune	300	125	58.3%
6	Hyderabad	5000	300	94%
7	Bangalore	3500	750	78.5%
8	Chennai	2500	1200	52%

Table 1: Construction & Demolition (C & D) Waste Volume and Efficiency of Recycling Plants in India

II. LITERATURE REVIEW

Waste material can also be considered as valuable, it can derive some materials which are reusable. The reuse of demolition waste for construction activities has long past. Recently, properties of these materials are carefully investigated to get consistent grade material in the form of aggregate or fine powder. It is estimated that by breaking down 1m^2 area of building results into 0.5 to 1 m^3 of C&D waste. And every 10,000 m^2 construction will eventually result into 500 to 600 tons of C&D waste [32]. In U.S. more than 20 states have started used of C&D waste in pavement construction activity [33]. C& D waste incorporated with stabilized fibers were used to improve performance during flexural fatigue behaviour of road base material [34].

Crushed bricks, reclaimed bitumen from existing scrapped pavements, excavated soil, rocks, fine broken glass etc has successfully tried as sub base material in new pavement construction [35, 36]. Construction waste and demolition waste was used for construction of base course in concrete pavement. CBR test results of recycled aggregates derived from demolition waste showed reduced bearing capacity of material. Hence provision of extra thickness is requiring to be provided. Whereas concrete crushed to get aggregates give fair results for CBR test and was recommended by investigator.

Partially replacing natural aggregates with recycled aggregates was investigated. Performance characteristics of blended mix up to 30% replacement with recycled aggregates gave fair results. Beyond 35% addition of recycled aggregates showed reduction in strength parameters. Blend of recycled construction aggregates (RCA) and recycled clay masonry (RCM) was used as sub-base material. During investigation pH of blend mix was more alkaline than natural aggregates, greater than seven [37, 38].

Demolition waste consisting bricks bats and crushed masonry was used to prepare recycled aggregates within crushers. Physical and mechanical properties of prepared recycled aggregates was assessed which showed that compactive effort applied during construction of base course of road pavement has major influence of behavior of this material. Although grading and quality of material within recycled aggregate is important, still density and packing of material at in-situ position is important in deciding the strength of material. Effect of moisture on strength of base and sub-base layer was investigated [9]. As shape and size of reclaimed aggregates from C& D waste affects optimum moisture content, maximum dry density and resulting compactive effort of layer was analysed in past [39]. Compaction causes partial breaking of material, changes shape and size of aggregates. It causes densification of layer, improves bearing capacity, resilient modulus and provides resistance to permanent deformation [40, 41, 42].

Presence on foreign material with demolition waste can severely affect the quality of prepared recycled aggregate. During demolition activity careful monitoring is required to avoid mixing of metallic, wooden and plastic particles in the aggregates. Otherwise during compaction activity, it will show sharp variation in the values of dry density and load carrying capacity of material.

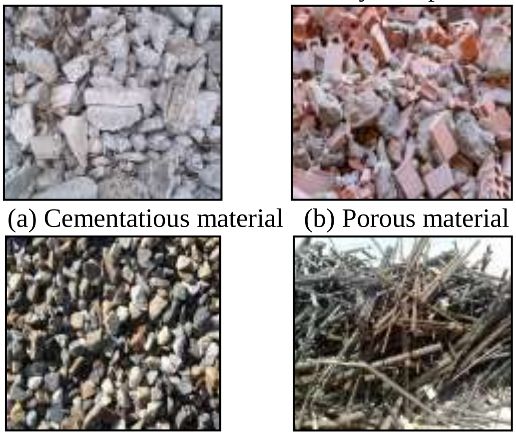
Use of recycled aggregates in construction of low and medium traffic roads has successfully investigated and it gave fair results for application in base and sub base layers. The strength and material properties need to be investigated in detail in order to decide its use as aggregated for construction of rigid pavement slab.

III. MATERIAL PROPERTIES

A. *Physical properties*

1) *Ingredients:*

Derived recycled aggregates were sieved through set of IS sieve. Aggregate passing through 20 mm sieve and retained on 4.75 mm IS sieve was used for further investigation. Based upon visual inspection it was deduced that basically recycled aggregates are composed of materials like cementitious material consisting of concrete and mortar, porous material from ceramic roof tiles and bricks, crushed stone metal, concrete tiles, organic materials like wood, paperboard as shown in fig 3. Inorganic materials like plastic, metal, steel etc is considered undesirable for the aggregates as it may alter the properties of aggregates which are supposed to be used in the construction of base and sub-base layer of pavement.



(a) Cementatious material (b) Porous material

(c) Crushed stone (d) Metals & plastics

Fig. 3: Types of RCDW wastes

Ingredients	% by weight	Water absorption rate	Particle shape
Cementitious material	59	11.2	Round, cubical
Porous material	12	18.4	Flaky and elongated
Crushed stone and tiles	25	5.6	Round and flaky
Plastic, wood and metal	4	2.1	elongated

Table 2: Physical Characteristics of Recycled Aggregates

2) Moisture content:

During construction it is recommended to use aggregates at saturated surface dry (SSD) condition to avoid fluctuations in water content in the concrete mix. In case of road construction recycled aggregates will be spread and compacted to maximum dry density at particular optimum moisture content. It is evident that recycled aggregates derived from construction and demolition waste has rough texture and more voids ratio. Their water absorption rate is more as compared to natural aggregates [43]. Presence of ceramic tiles and brick bats in recycled aggregates has even more absorption rate and hence the content of porous material with recycled aggregates has to be kept limited by carefully monitoring the source of waste and avoid it mixing with recycled aggregates prepared for construction of pavement. Moisture content of recycled aggregates was found to 15.3% more than virgin aggregates used in base course. Presence of loose mortar and concrete sticking to aggregates in RCA increases its water absorption rate and decreases density.

3) Particle shape and grain size distribution:

RCDW sample sieved through set of sieves as per IS 2720 (Part-4). Particle size distribution curve was plotted for particle size versus percentage of sample passing particular sieve size. The graph shown in fig. 4 gives nature of sample available for study. The graph indicates uniform grading of recycled aggregates. As compared to natural aggregates percentage of fines is more in case of recycled aggregates. During test the percentage of fines have major influence on strength of prepared base layer. It was evident that presence of fines in waste will increase the performance of prepared base layer upon proper compaction. It will reduce permeability of layer and provide dense packing of aggregates. All pores are filled with particles. Depending on type of recycled aggregates, porous material waste absorbs more moisture and reduced strength of layer. It was evident that angular shaped aggregates derived from RCDW requires more effort during compaction as compared to natural aggregates.

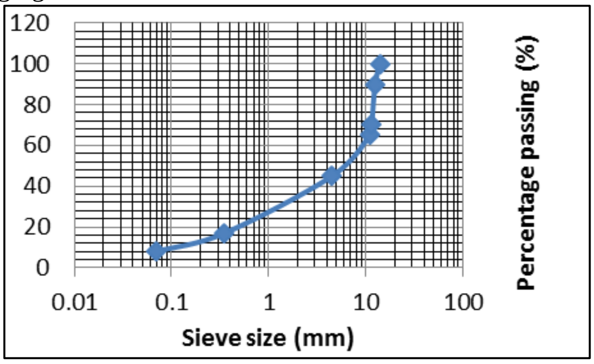


Fig. 4: Particle Size distribution Curve for RCDW aggregates

B. Mechanical Properties-

Extensive laboratory testing performed to assess the given sample compromising of RCDW. Test results were further validated by corresponding field tests. Physical and engineering properties of prepared recycled aggregates assessed to decide its suitability in construction of pavement. Mechanical properties like density, compactive effort, plastic deformation, resilient modulus and CBR values examined and conclusions based upon test results.

1) Compaction test:

Standard compaction test and modified compaction test was performed on RCDW material since it was supposed to be used as ingredient of base course. Test was performed as per IS: 2720 Part 7- 1980. Past literature reveals that RCDW properties are variable and difficult to obtain smooth curve. In present investigation for different values of moisture content, dry density values are computed and plotted suitably to find Maximum dry density (MDD) and optimum moisture content (OMC) value from standard curve and modified proctor curve. Further investigation requires these values. Natural aggregates have high MDD value and lowest OMC since they are less porous and highest particle density. Whereas recycled aggregates have nearly double OMC values and comparatively less MDD than natural aggregates [44]. Presence of adhered cement and mortar to aggregates reduces the density and increase moisture absorption. Thus it will avoid penetration of moisture to base in case of worst climatic conditions making its desirable material in road base construction [45, 46, 47]. Laboratory compaction test results can be evaluated by performing field proctor test using proctor needle and test results in case of given sample were confining to lab results.

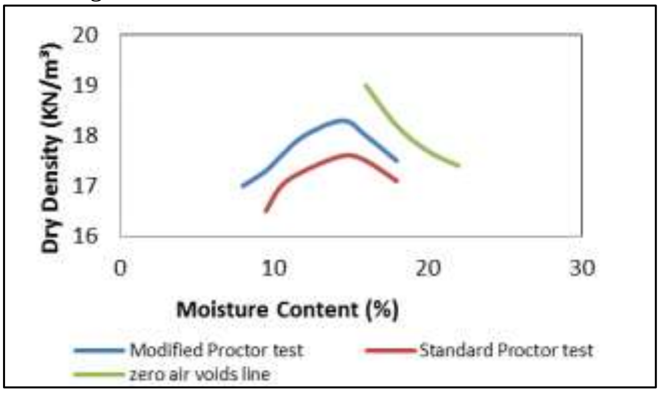


Fig. 5: Relationship between Dry density and moisture content for RCDW aggregate

2) Permeability:

Coefficient of permeability determined as per IS: 2720 part 17- 1986 will provide idea regarding nature of recycled aggregates. In case of natural aggregates falling head permeability test adopted to determine the permeability of material. Permeability value of recycled aggregates was found to less as compared to natural aggregates. Presence of fines on recycled aggregates has provided dense packing. It filled all pores and reduces the permeability value for prepared base layer in pavement construction.

3) California Bearing ratio (CBR) test:

CBR test gives indirect soil strength and specifies thickness of layer required to be provided as base course during construction of pavement. Test was performed as per IS: 2720 Part 16- 1987. CBR value of RCDW aggregate was estimated for sample prepared at OMC as determined during compaction test. 6 Test samples were prepared by mixing sample at OMC and compacting in mould of 15.2 cm diameter and 12.7 cm height at MDD. 4.5 kg surcharge weight was provided which acted as load similar to top layers on base course. The sample was subjected to loading under loading frame and corresponding deflection values were measured. CBR value gives bearing capacity of sample by comparing with standard crushed stone. Average CBR value for RCDW sample under investigation was found to be 85% of natural aggregates. Although variation of 15 % still fair enough bearing capacity can be obtained by increasing the thickness of base course during construction of road pavement. Sample was also investigated by subjecting prepared mould to four days soaking and found to decrease in CBR value by 8.5% which shows slight to negligible variation in values. This is the critical situation, where pavements are subjected to saturation during rains and subsequent runoff. The RCDW sample under investigation is found to be durable enough to face the critical situation of saturation point and perform satisfactorily.

4) Plate Load test:

Testing was performed by compacting Recycled aggregates in iron test box of 1m x1m x 1m size at OMC and MDD. Relative density achieved is measured with sand cone test. The gradual deflection corresponding to applied pressure is measured at 30 minutes intervals till maximum deflection is achieved and corresponding graph plotted accordingly.

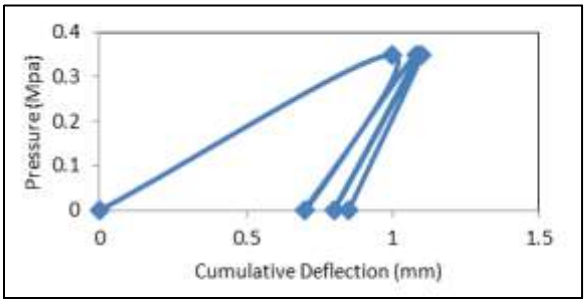


Fig. 6: Plate load test investigation on RCDW aggregates

Further applied pressure is released and material is allowed to regain to original position. This repetition is done 3 times in order to obtain bearing capacity of recycled aggregates which are to be used as base material. Experimental investigation indicated that maximum deformation under applied pressure occurs in first cycle as compared to second and third cycle as shown in fig. 6.

5) Resilient modulus:

Depending of test results, resilient modulus (Mr) in case of recycled aggregates show increase in value with increase in compressive stress. Mr Value is considered superior than CBR test, since confinement stresses are considered in triaxial test and neglected in CBR test. And displacement values were recorded only within elastic range as compared to CBR test which continues to measure deflection value upto end of test. Resilient modulus derived as per [48] as,

$$\mathbf{M_r = \frac{\pi(1-\mu^2)p \times a}{2\omega}}$$

Where, Mr = Resilient modulus (MPa),
P= Uniform applied pressure (MPa),
a= radius of circular plate (mm),
ω = Deflection measured in plate load test (mm)
μ = Poisson's ratio of aggregates

The test results indicated resilient modulus value for recycled aggregates ranging from 200 to 450 MPa for corresponding bulk stress 0.2 to 0.9 MPa. This value is 12 to 21% higher than that of natural aggregates. Resilient modulus value is time dependent and increase with time period [49]. Shape of recycled aggregates and corresponding internal friction between particles contributes to increase in shear strength values while performing triaxial test.

6) Permanent deformation:

During triaxial test, loading cycle is repeated. It includes gradual application of load and measuring corresponding deflection. During unloading phase also measure regain in length of specimen. But continuous loading cycle brings about some amount of permanent deformation in the specimen. By varying application of deviator and confining stress, corresponding value of deflection is measured. These values are found to show rising trend based upon number of loading cycles. Fig.7 gives rising trend in curve for corresponding loading cycles.

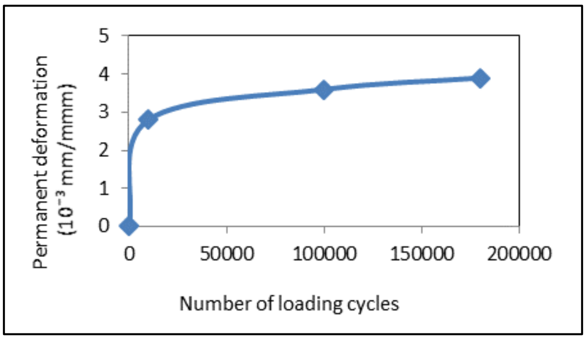


Fig. 7: Permanent deformation for Recycled aggregates

IV. CONCLUSION

Detailed laboratory investigation of available construction and demolition (C&D) waste was performed based upon standard selection procedure consisting material of different gradation to obtain fair results. Based upon test results following conclusions are drawn:

1) Based upon material source, water absorption values varied. Waste materials derived from porous roof tiles, ceramic tiles, bricks shown significantly high water absorption rate as compared to concrete waste. Concrete waste having regular grain size showed less value as compared to irregular grain size of concrete waste due to dense packing while avoided flow of water in between interconnected pores. It is preferable to use porous material for base course in pavement construction so that rainwater percolating through road surface will drain away easily. Demolition waste is an effective alternative for aggregates and stone metal in laying of base course during road construction.
2) Particle size distribution curve plotted similar to aggregate in order to determine grading of particles. In case of RCDW particle size distribution follows different pattern. It was found that due to compaction, partial crushing and breakage of particles was observed that could change the grading of particles. Uniform grading of particles is desirable which consist particles of all size range. But in case of construction and demolition waste, particles derived were more or less or same size, thus uniform grading pattern was found in curve. It will reduce the packing ability and thus load bearing capacity of prepared base course as a whole.
3) During road construction base layer consisting of RCA derived from C&D waste is compacted in layers by passing pneumatic rollers over the layers. With increase in number of roller passes the compaction effort increases and porosity values of sample decrease. It indicates that gap between coarse particles in RCA are filled by fines obtained during crushing of loose adhered mortar or concrete within the C&D waste. Also with increase in thickness of base layer the effect of compactive force on C&D waste material placed in lower layers of base decreases and the layer remains loose. Generally 20 mm thick base layer is recommended after extensive investigation.
4) CBR test values gives indication of strength of particles and decide the thickness of layer to be provided. In case of natural aggregates the CBR value compared with crushed stone give fair result whereas in case of recycled construction and demolition waste used as replacement to aggregates shows variation in CBR value. Efforts are required to obtain consistent CBR value for RCDW particles to design thickness of base and sub base course consisting of RCDW particles. In case of soaked sample, CBR value is same as moist sample. Negligible variation was observed in both values.
5) Natural aggregates as well as RCDW particles were compared to obtain resilient modulus. It was observed that on increase in compactive effort on aggregates as well as RCDW particles the value found to increase by 12 to 18%.
6) Loading pattern and corresponding displacement values show high strength property of natural aggregates which makes them most desirable material for load bearing base course layer. But in case of RCDW the loading pattern in linear as compare to displacement values. Initially particles showed good resistance to deformation under application of gradual load. But beyond certain load value failure of material was found in case of plate load test. Minimal plastic deformation and maximum resilient modulus observed in case of recycled aggregates. The test results indicate use of RCDW particles to be kept limited to pavement having light to medium traffic. Still extensive research work will be required to obtain material having consistent strength and quality.

Thus comparing physical and mechanical properties of natural and RCDW particles it could be concluded that these waste materials can be accommodated in the pavement construction. Careful monitoring in required to check these material are obtained of good quality and consistency in maintained in properties. Any compromise in the material may lead to heavy loss of life and property.

REFERENCES

[1] Asgari, T. Ghorbanian, N. Yousefi, D. Dadashzadeh, F. Khalili, A. Bagheri, M. Raei, AM Mahvi, “Quality and quantity of construction and demolition waste in Tehran”. Journal of Environmental Health Science & Engineering, 2017, vol. 15(14).

[2] Poon CS, D Chan, “The Use of recycled aggregate in concrete in Hong Kong”. *Resources, Conservation and Recycling*, 2007, vol. 50(3), pp. 293–305,

[3] Herrador R, Perez P, Garach L, Ordonez J, “Use of recycled construction and demolition waste aggregate for road course surfacing”, *Journal of Transportation Engineering*, 2012, vol. 138 (2), pp. 182–190.

[4] Hendriks CF, Janssen GMT, “Reuse of construction and demolition waste in the Netherlands for road constructions”, *Heron*, 2001, vol. 46(2), pp. 109–117.

[5] Bansal A, Mishra G, Bishnoi S (2016) Recycling and reuse of construction and demolition waste: sustainable approach. 7th International conference on sustainable build Environment 2016, Kandy Srilanka, 7.

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

[7] O'Mahony MM, Milligan GWE (1991) Use of recycled materials in sub-base layers. Transportation Research Record, 1310: 73–80.
[8] Poon CS, Chan D (2006) Feasible use of recycled concrete aggregates and crushed clay brick as unbound road sub-base. Construction and Building Materials, 20(8): 578–585.
[9] Park T (2003) Application of construction and building debris as base and sub-base Materials in Rigid Pavement. Journal of Transportation Engineering, 129(5): 558–563.
[10] Jimenez J, Ayuso J, Agrela F, Lopez M, Galvin AP (2012) Utilization of unbound recycled aggregates from selected CDW in unpaved rural roads. Resources, Conservation and Recycling, 58: 88–97.
[11] Umar UA, Shafiq N, Malakahmad A, Nuruddin MF, Khamidi MF (2017) A review of the adoption of novel techniques in construction waste management and policy. Journal of Material Cycles and Waste Management, 19(4): 1361–1373.
[12] *Broujeni BR, Omrani GA, Naghavi R, Afraseyabi SS* (2016) Construction and demolition waste management (Tehran Case Study). Engineering, Technology & Applied science research, 6(6):1249-1252
[13] Vieira CS, Pereira PM (2015) Use of recycled construction and demolition materials in geotechnical applications: A review. Resources Conservation & Recycling, 103: 192–204.
[14] O'Mahony MM (1997) An analysis of the shear strength of recycled aggregates. Materials & Structures, 30(599).
[15] Bergsdal H, Bohne RA, Brattebo H (2008) Projection of construction and demolition waste in Norway. Journal of Industrial Ecology, 11(3):27–39.
[16] Jia X, Ye F, Huang B (2015) Utilization of construction and demolition waste in low volume roads for rural areas in China. Transportation research record, 2474(1):39-47.
[17] Mihai FC (2019) Construction and Demolition Waste in Romania: The Route from Illegal Dumping to Building Materials, Sustainability,11(11):3179.
[18] Molenaar AAA, van Niekerk AA (2002) Effects of gradation, composition, and degree of compaction on the mechanical characteristics of recycled unbound materials. Transport Research Record, 1787(1):73–82.
[19] Singhal S, Pandey S (2001) Solid waste management in India: Status and Future directions. TERI Information Monitoring on Environmental Science, 6(1):1-4.
[20] Kryckyj PR, Triches G (2000) Use of civil construction waste in urban pavements: A feasibility study. In: Proceedings of the 5th international symposium on environmental geotechnology and global sustainable development.
[21] Li Y, Sun X, Yin J (2010) Mix design of cement-stabilized recycled aggregate base course material. GeoShanghai International Conference 2010.
[22] Ram VG, Kalidindi SN (2017) Estimation of construction and demolition waste using waste generation rates in Chennai, India. Waste Management & Research: The Journal of the international solid wastes and public cleaning association, ISWA, 35(6): 610–617.
[23] Cochran K, Townsend TG, Reinhart DR, Heck H (2007) Estimation of regional building-related C&D debris generation and composition: case study for Florida. US Waste Management, 27(7):921–31.
[24] Nokkaew K (2018) Characterization of recycled aggregate for use as base course material. International Journal of GEOMATE, 15(48):129-136.
[25] TIFAC, Ed. (2001) Utilization of Waste from Construction Industry. Department of Science & Technology, New Delhi.
[26] Kofoworola OF, Gheewala SH (2009) Estimation of construction waste generation and management in Thailand. Waste Management, 29(2):731–8.
[27] Li M, Kuhlen A, Yang J, Schultmann F (2013) Improvement of the statutory framework for construction and demolition waste management exemplified in Germany and Australia. Urban Environment. Springer Netherlands:15–25.
[28] Shen LY, Tam V (2002) Implementation of environmental management in the Hong Kong construction industry. International Journal of Project Management, 20(7): 535–43.
[29] Vazquez E (2013) Overview regarding construction and demolition waste in several countries. Progress of Recycling in the Built Environment. Springer Netherlands:37–173.
[30] Macias A, Piniarsk W (2016) Municipal solid waste management problems on a local scale: A case study from rural Poland. Polish Journal of Environmental Studies, 25(4):1623–1632.
[31] Guignot S, Touze S, Weid F, Menard Y, Villeneuve J (2015) Recycling construction and demolition wastes as building materials a life cycle assessment. Journal of Industrial Ecology,19(6):.
[32] Yuan H, Shen L (2011) Trend of the research on construction and demolition waste management. Waste Management, 31(4).
[33] Ekanayake LL, Ofori G (2004) Building waste assessment score: design-based tool, Building and Environment, 39(7): 851–861.
[34] Sobhan K, Krizek RJ (1999) Fatigue behavior of reinforced recycled aggregate base course. Journal of Materials in Civil Engineering, 11(2):124–130.
[35] Arulrajah A, Piratheepan J, Aatheesan T, Bo MW (2011) Geotechnical properties of recycled crushed brick in pavement applications. Journal of Materials in Civil Engineering, 23(10): 1444-1452.
[36] Arulrajah A, Jegatheesan P, Bo MW, Sivakugan N (2012) Geotechnical characteristics of recycled crushed brick blends for pavement sub-base applications. Canadian Geotechnical Journal, 49(7): 796-811.
[37] Arisha A, Gabr A, El-Badawy S, Shwally S (2016) Using blends of construction & demolition waste materials and recycled clay masonry brick in pavement. Advances in Transportation Geotechnics, The 3rd International Conference on Transportation Geotechnics, 143: 1317–1324.
[38] Poon CS, Qiao X, Chan D (2006) The cause and influence of self-cementing properties of fine recycled concrete aggregates on the properties of unbound sub-base. Waste management, 26(10): 1166-1172.

[39] Paige-Green P (2003) Strength and behavior of materials for low-volume roads as affected by moisture and density. Transportation Research Record,1819(1).
[40] Wu S, Zhong J, Zhu J, Wang D (2013) Influence of demolition waste used as recycled aggregate on performance of asphalt mixture. Road Materials and Pavement Design, 14(3):679-688.
[41] De Farias MM, Gomez A, Sinisterra FQ (2013) Use of recycled aggregates from construction and demolition wastes for the construction of flexible pavements. Third International Conference on Geo-technique, Construction Materials and Environment, Nagoya, Japan.
[42] Gabr AR, Cameron DA (2011) Properties of Recycled Concrete aggregate for unbound pavement construction. Journal of Materials in Civil Engineering, 24(6):754–764.
[43] Ayan V, Limbachiya MC, Omer JR, Azadani SMN (2014) Compaction assessment of recycled aggregates for use in unbound sub-base application. Journal of Civil Engineering and Management, 20(2): 169–174.
[44] El-Maaty Behiry AEA (2013) Utilization of cement treated recycled concrete aggregates as base or subbase layer in Egypt. Ain Shams Engineering Journal, 4(4):661-673.
[45] Jayakody S, Gallage C, Ramanujam J (2019) Performance characteristics of recycled concrete aggregate as an unbound pavement material. Heliyon, 5(9).
[46] Hu L, Hao J, Wang L (2014) Laboratory evaluation of cement treated aggregate containing crushed clay brick. Journal of traffic and transportation Engineering, 1(5):371-382.
[47] Tahmoorian F, Samali B (2018) Laboratory investigations on the utilization of RCA in asphalt mixtures. International Journal of pavement research and technology, 11(6): 627-638.
[48] Melbouci B (2009) Compaction and shearing behaviour study of recycled aggregates. Construction and Building Materials, 23(8): 2723–2730.
[49] Arulrajah A, Jegatheesan P, Bo MW, Ali MMY (2012) Geotechnical properties of recycled concrete aggregate in pavement sub-base applications. ASTM Geotechnical Testing Journal, 35(5):1–9.
[50] Ping WV, Sheng B, Ling CC, Dietrich B, Horhota D (2010) Influence of Base clearance on sub-grade resilient modulus of florida roadway pavements. Transportation Research Board, 2154(1).
[51] Rahman M, Gassman SL (2018) Moisture Effect of subgrade resilient modulus on pavement rutting. Conference: Transportation Research Board 97th Annual Meeting.
[52] Yadhu G, Devi SA (2015) An innovative study on reuse of demolished concrete waste. Journal of Civil & Environmental Engineering, 5:185.
[53] Li Y, Zhou H, Su L, Hou H, Dang L (2017) Investigation into the application of construction and demolition waste in urban roads. Hindawi Advances in Materials Science and Engineering,
[54] Rodrigo EC, Jose da CMN, Cristine DS, Erica P, Valdir S (2017) Alternative construction and demolition (C&D) waste characterization method proposal. Sanitary Engineering Journal, 24(1): 199-212,
[55] Hendriks CF, Janssen GMT (2003) Use of recycled materials in constructions. Materials and Structures, 36:604–8.
[56] Hansen TC (1986) Recycled aggregates and recycled aggregate concrete second state-of-the-art report developments 1945–1985. Materials and structures, 19: 201-246.
[57] Angulo SC, Miranda LFR, John VM (2002) Construction and demolition waste, its variability and recycling in Brazil. Proceedings of sustainable building, Oslo.
[58] Contreras M, Teixeira SR, Lucas MC, Lima LCN, Cardoso DSL, da Silva GAC, Gregorio GC, de Souza AE, dos Santos A (2016) Recycling of construction and demolition waste for producing new construction material (Brazil case-study). Construction and Building Materials, 123:594-60, https://doi.org/10.1016/j.conbuildmat.2016.07.044
[59] Asif Husain A, Assas MM (2013) Utilization of demolished concrete waste for new construction. World Academy of Science, Engineering and Technology International Journal of Civil and Environmental Engineering , 7(1):37-42.
[60] Rada G, Witczak MW (1981) Comprehensive evaluation of laboratory resilient moduli results for granular materials. Transport Research Record, 810:23–33.
[61] Nataatmadja A, Tan YL (2001) Resilient response of recycled concrete road aggregates. Journal of Transportation Engineering,127(5):450–3,
[62] Huang Y (2004) Pavement analysis and design. 2nd Edition Prentice Hall, Inc., Upper Saddle River, New Jersrey.
[63] Monismith CL, Ogawa N, Freeme CR (1975) Permanent deformation characteristics of subgrade soils due to repeated loading. Transport Research Record, 537:1–17.
[64] Sharp RW, Booker JR (1984) Shakedown of pavements under moving surface loads, Journal of TransportationEngineering,110(1):1-14
[65] Werkmeister S, Dawson AR, Wellner F (2001) Permanent deformation behavior of granular materials and the shakedown concept. Transportation Research Record, 1757(1):75–81, https://doi.org/10.3141/1757-09
[66] IS: 2720- Part 4 (1985) Methods of test for soils, Grain size analysis, Bureau of Indian Standards.
[67] IS: 2720- Part 7 (1980) Methods of test for soils, Determination of water content-dry density relation using light compaction, Bureau of Indian Standards.
[68] IS: 2720 part 17 (1986) Methods of test for soils, Laboratory determination of permeability, Bureau of Indian Standards.
[69] IS: 2720 Part 16 (1987) Methods of test for soils, Laboratory determination of CBR, Bureau of Indian Standards.

