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Recycled Aggregate in Pavement Construction: Review of Literatures

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Abstract-
The built environment consumes a lot of energy and material. A huge demand of about 40 billion tonnes of aggregates is demanded for construction purpose. The cost of material accounts for more than 60% of the total project cost. However, 10% of construction material end up as demolition wastes yearly. Aggregate is a beneficial building component in construction. There is much need to develop ways to ensure it is utilized properly as construction and demolition waste contribute a large percent to landfills. This review of literature examined the generation of construction and demolition waste generated in developed countries, waste characterization, and utilization in pavement construction. Additionally, environmental, economic and social benefits of the reuse of this waste was espoused. The result of the review revealed that The initial construction material quality, scale of the project, contract and construction mode used affect the amount and quality of CDW. CDW are bulky and not suitable for composting and incineration. Ultimately, the utilization of this waste would reduce the amount of raw material used in construction leading to conservation. Also, there would be reduction in the energy cost associated with mining (quarrying), extraction and transportation of natural aggregates in track with the conservation of natural resources and the construction of cost-effective pavements.

Key words: Construction and demolition waste, Recycled aggregates, Pavements, strength properties.

1. Introduction

Built environment expand every day. The continuous expansion and reconstruction of the built environment lead to a huge consumption of energy and generation of wastes. The continuous expansion require huge amounts of construction materials [1]. In the EU, construction industry utilizes 40% of the total energy consumption. Furthermore, it generates 30% of the total CO_2 emission [2]. Astoundingly, it has been estimated that up to 10% of the construction materials become construction wastes. There are various factors responsible for this waste generation. They include over-ordering or over estimation, design and/or construction changes, damages and loss. These wastes have been estimated to amount to 20 to 30% of the total building weight. To renovate or rebuild, demolition takes place.
In UK, 120 million tonnes of CDW are generated annually. Whereas in the USA, about 140 to 534 million tonnes of CDW are produced annually [3][4]. Japan generates more than 77 million tonnes

of CDW annually [5]. Globally, about 3 billion tonnes of CDW are generated annually. [6] estimated that 7000 million tonnes of CDW have being acuminated in China, over the years. Conversely, over 300 million tonnes are generated annually in China. The contribution of CDW to the total solid waste varies from country to country.
Gloomily, most of these wastes are usually open dumped in most developing posing serious environmental problems. Hence, this review of literatures examined the amount of construction and demolition waste generated in some selected countries. Additionally, waste characterization, recycling, utilization, environmental impact, economic and social benefits of the reuse of this waste was assessed in track with sustainable development goals.
Different statistics have stated that the construction and demolition wastes (CDW) account for a huge amount of the total solid waste as depicted in Fig 1 and 2 [7]. CDW account for 25% of the solid waste generated in India and Europe [8]. In England, CDW account for 32%, whereas in Hong Kong, it represents about 40 % of the total waste generated. The impact of this waste stream is observed in the amount disposed in the landfill. Statistics from Europe showed that up to 75% of the CDW are landfilled [7].
Data of developing countries CDW generation are scare with few countries have reliable data. It can be approximated that CDW in Tanzania and South Africa about 8 million tonnes [9][10]. Researchers in developing countries are aware of the challenges associated with CDW. Mostly lack of data, policy and waste management in developing countries. They rely on developed countries' data for their studies.

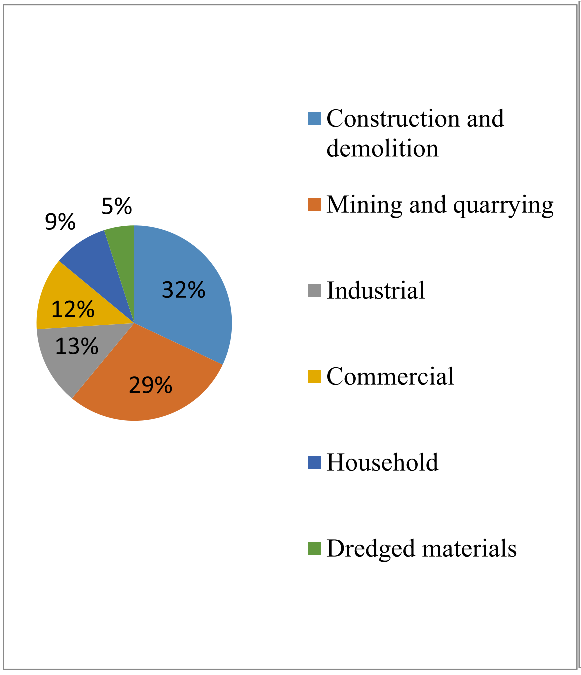

Fig 1: waste generation UK adopted from [7]

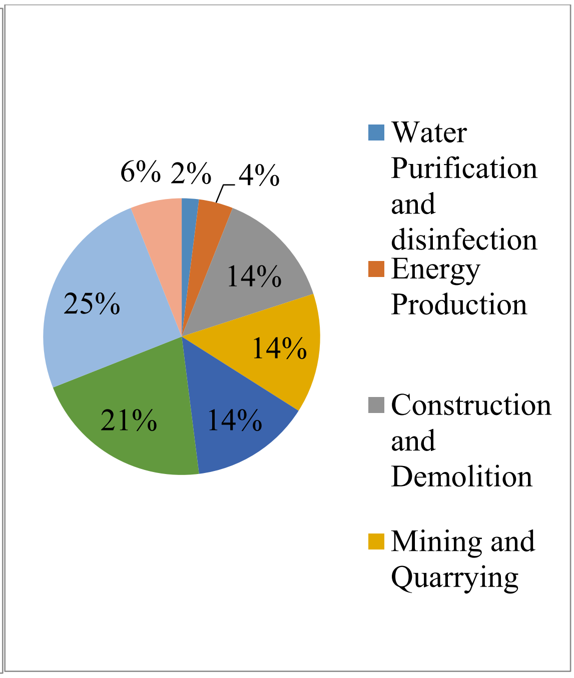

Fig 2: waste Composition OECD regions.

CDW consist of various materials such as PVC pipe, aluminium siding, asphalt, brick, concrete, lumber, woody debris and wallboard. Construction wastes are sourced from different categories: design, procurement, handling of materials, operation, residual and other sources. Demolition wastes are from complete or selective demolition. The waste quality and quantity differ from site to site. The initial construction material quality, scale of the project, contract and construction mode used affect the amount and quality of CDW. As shown in Fig 3. high rise building accounts for most of the CDW [11]. Demolition wastes are easier to recycle as there is relative homogeneity of the materials. The large amount of metals, concrete and brick can be collected readily as sorting is easier. Some products, such as pipes and woods can be sold on the spot.

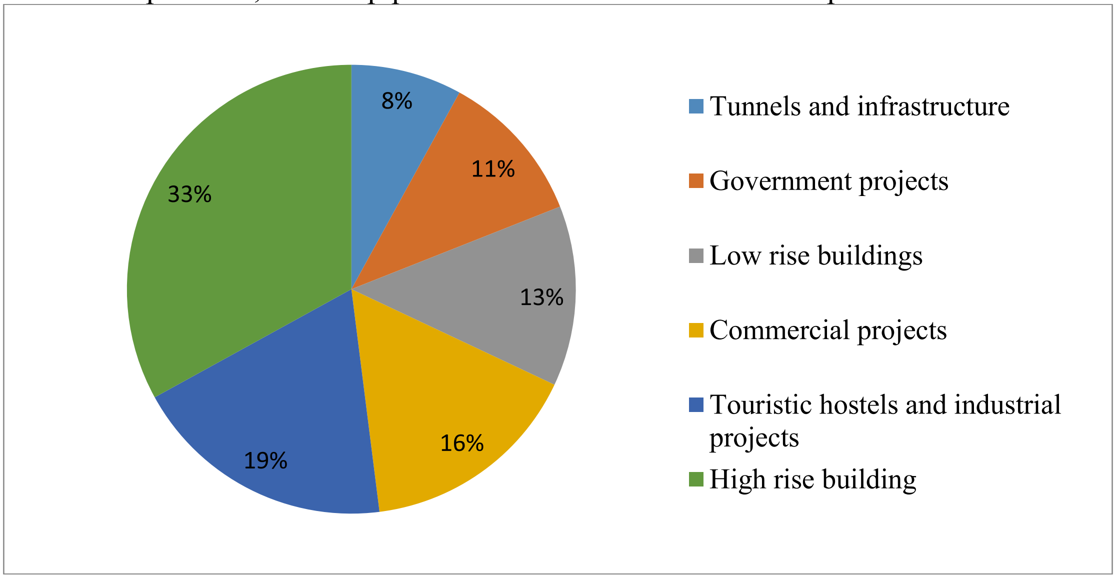

Fig 3: cumulative percentages of projects generating construction waste in Egypt adopted from [11]

2. Reuse of construction and demolition waste

The reuse of this waste is necessary. Improper disposal of CDW creates an ugly site and cause environmental issues [12]. Consequently, it leads to economic losses, and contamination of the groundwater through leaching [11]. In addition, CDW are bulky and not suitable for composting and incineration. Furthermore, the utilization of this waste would reduce the amount of raw material used in construction leading to conservation. Also, there would be reduction in the energy cost associated with mining (quarrying), extraction and transportation of natural aggregates [13]. Furthermore, there are other economic benefits attached to successful recycling [14]. This prompted developed countries to reuse CDW in various sector including road construction. Consequently, the rate of reuse is increasing in developed countries.

It has being established that several tonnes of materials are needed for road construction. Aggregate in asphalt pavement commonly used in developing countries comprises of up to 95% natural aggregates. The total amount needed for a project depends on the road's subgrade and expected traffic loading and the projects size. From the golden rule of waste management, reduction is first. For weak subgrade (< 10% CBR), stabilization using waste can be done [15][16]. This would significantly reduce pavement thickness and the amount of materials needed for construction. Next is the application of reuse. Several research have scientifically proven that recycled aggregate can be used in pavement construction. This provides economic, environmental and social benefits.

Reclaimed asphalt pavement (RAP), recycled concrete aggregate (RCA) and recycled aggregate (RC) from CDW can be used in pavement interlayers (sub-base and base) [8]. Likewise, powdered RCA, RC and bricks can be used as asphalt filler. Looking as the waste characterization from various countries as illustrated in Table 1 and 2, and Fig 4, Excavated soil, concrete and Brick are predominant. They will be generally referred to recycled aggregate in this review.

Table 1: constituents of Waste that Arise from CDW in India adopted from [1]

Constituent	Quantity generated in Million Tonnes
Sand and gravel	4.20 to 5.14
Brick	3.60 to 4.40
Concrete	2.40 to 3.67
Metals	0.60 to 0.73
Wood	0.25 to 0.30
Others	0.10 to 0.15

Table 2: estimated Range of Wastes by Material Type from the Egyptian Construction Sites adopted from [11]

Material	Average %
Wood/lumber	11.5
Excavated soils	36
Steel	8
Concrete	7
Mortar	10
Bricks	9
Concrete blocks	10
Plastics	4
Ceramics	9.5
Chemicals	2.5
Minerals	2.5
Prefabricated units	5
Mixed waste	25
Marble/Granite	2
Cables, ducting and pipes	17.5
Corner bead	1
Glass	0.5
HVAC insulation	4

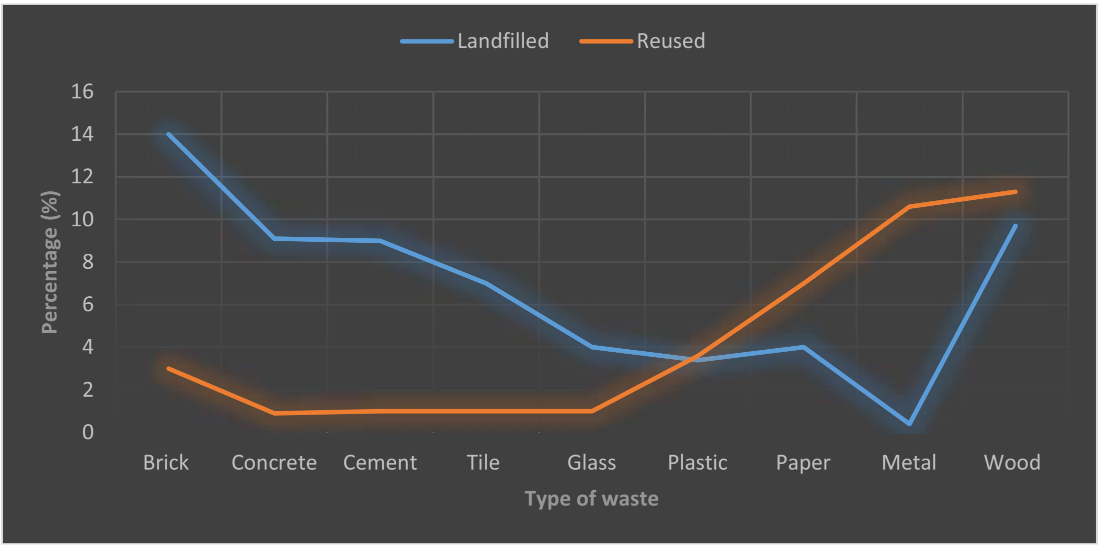

Fig 4: waste profile and management from Thailand construction project [17]

2.1 Aggregate demand

According to the annual review by European aggregates association, 2.6 to 3.2 billion tonnes of aggregates are produced annually [18]. This indicate that recycled aggregate accounts for only 8%. Consequently, demolition waste accounts for 40% of the recycled aggregate. Conversely, [19] reported that globally 40 billion tonnes of aggregates are produced annually. China produces 38% of the total global production followed by India at 13 and the rest of Asia accounting for 12% as illustrated in Fig 5. [18] highlighted that for every 1 km of roadway, 30,000 tonnes of aggregate is needed.

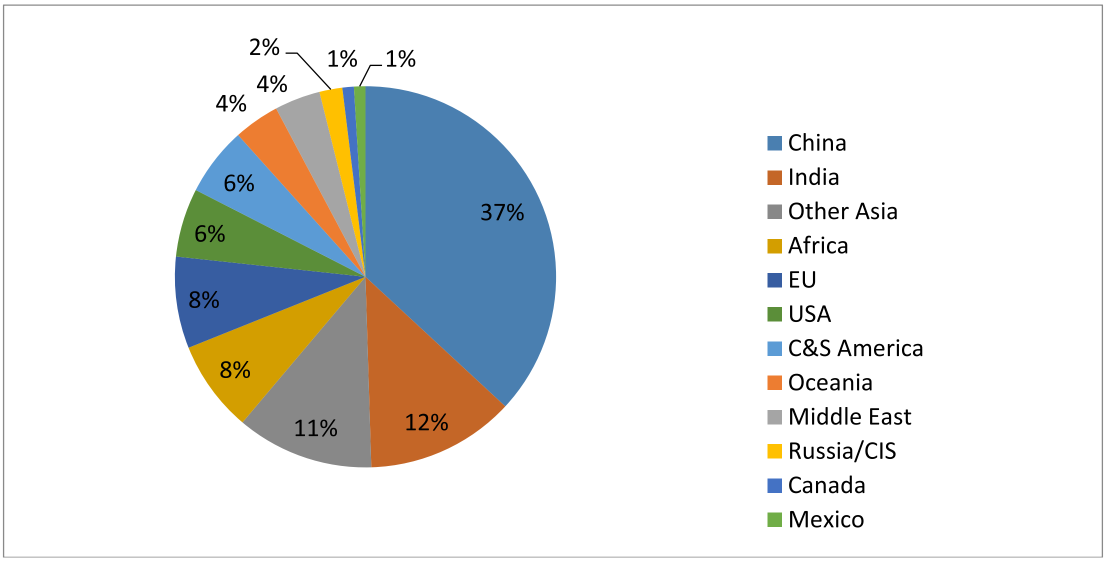

Fig 5. global aggregate production.

2.2 Recycled aggregate for pavement construction

Suitable excavated soil that is not problematic soil can be reused. For the production of the RC without impurity in the required gradation, a production plant has to be used. This can either be stationary or mobile. However, both consist of the same setup which includes separation, crushing, separation and removal of ferrous elements, screening, decontamination and removal of impurities as shown in Fig 7 [20]. Mobile can help reduce transportation cost [19]. Stationary provides a known point where RC can be purchased by all and sundry.

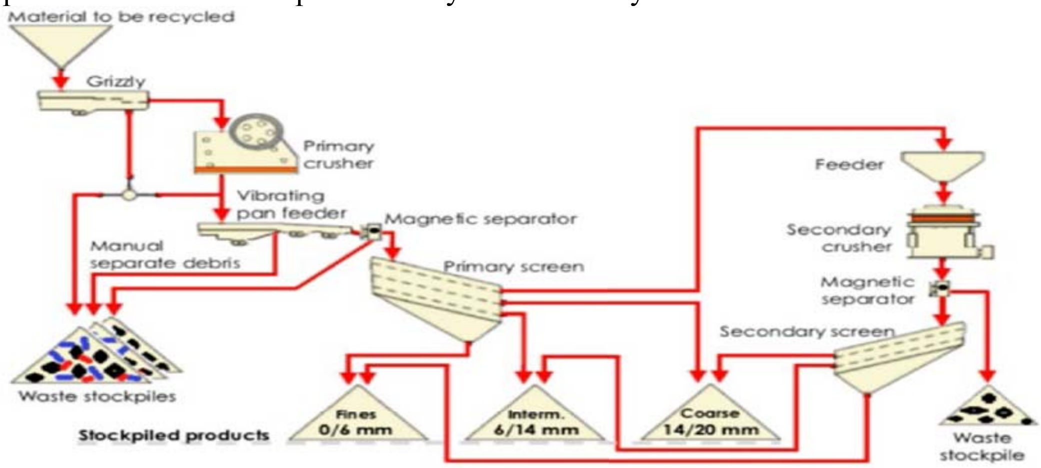

Fig 6: typical RC processing plant [3].

The suitability of any aggregate for pavement interlayer is based on certain characteristics. They include the gradation, angularity, soundness and solubility [21]. Typically, recycled aggregates have lower relative densities as well as high water absorption of about 2 to 10% [22] [23]. This is due to the presence of mortar surrounding the aggregate and masonry. Also, the presence of micro cracks due to second crushing, collision, and sliding during processing affects these aggregates. Furthermore, RC have lower crush values and adhesion levels [24]. Also, RC have lower Los Angeles coefficient, Optimum moisture content (OMC) and Maximum dry density (MDD). RC (RAC) possesses lower flakiness index. The shear strength of RC and natural aggregate (NA) are not significantly different. However, RC are more susceptible to particle crushing, which is subjective to the vertical pressure and number of loading cycle [25].
Different countries have designed various specification and guidelines for the use of RC in pavement structure. These specifications differ from each other considerably. Different standards use traffic load, field trial, experience, material purity or material properties to classify RC. Specification include VicRoads, Department for Transport, Energy and Infrastructure (DTEI), Institute of Public Works Engineering Australia (IPWEA), New South Wales (NSW), Roads and Traffic Authority (RTA), NSW, and Main Roads West- ern Australia (MRWA), Dutch specification, Finland specification [26]. A lot of work needs to be done to provide a detail workable specifications as most are limited. For example, some specification such as Finland and DTEI specification do not account for CBR. Developing countries have not written and public their own specification. [27] argued that even without a clear specification, the use of RC is viable and cost effective.
[28] evaluate the use of various types of CDW. The study compared the RAC, crushed brick (CB), RAP, waste excavation rock (WR), fine recycled glass (FRG) and medium recycled glass (MRG). The investigation examined various tests such as gradation, Los Angeles Abrasion, unconfined compression, California Bearing Ratio (CBR), direct shear and consolidated drained triaxial tests. The test indicated that WR, FRG and MRG had high resistance, which are required as an interlayer material. Apart from RAP, other had LA abrasion values less than 40. In term of durability in

soaked conditions, RCA, CB and WR, had high CBR values higher than 80 and 100. The study recommended the use of RAP, FRG and MRG for subbase and base layer.

[23] investigated the possibility of mixing different recycled aggregate. The study revealed that recycled aggregates are not always homogenous. They consist of various type of material. RAC might consist of ceramic materials, or bricks. Therefore, a study to examine the effects of various wastes was designed. The use of different processing systems was observed. The results showed that out of the 23 materials tested, 14 met the Spanish regulation of Los Angeles coefficient less than 40. Also, others only failed narrowly. The study also showed that RC had high CBR values. The study encourages the use of RA with less than 25% masonry for subbase application.

Furthermore, [29] investigation reported that there is no significant variation in compressive strength, flexural strength and split tensile strength of concrete made with RC and NA. However, it stated that there was increase in water absorption as well as reduced modulus of elasticity and resistivity. The author concluded that concrete mixtures needed for pavement construction can use RC but long field performance test should be carried out.

[30] also examined the impact of RC (RCA) on asphalt concrete. The investigation revealed that resilient modulus of asphalt containing RC reduced as binder was added. The values obtained with RC were lower than the control. However, the results are still within the acceptable limits prescribed by the Austroads pavement research Group. Stripping potential is higher with RC. There are significant variations in strength under moisture conditions. The study recommended a more comprehensive research into various samples or content of RCA as it is viable.

A review by [31] mentioned that several works had been done by [32-35] through laboratory test. The authors concluded that RC is suitable for pavement interlayer. Ranging from CBR tests, permanent deformation properties, resilient response, degree of compaction, gradation, shear resistance and stability, examined by several researcher from various countries, they all recommended the use of RC in pavement construction. However, the review mentioned that soundness test for recycled materials would not be accurate. It was revealed that cement mortar would adhere to the aggregate which would increase the loss in soundness test.

[22] carried out a field trial to test the performance of recycled aggregate to natural aggregates. The study showed that the use of recycled aggregate during construction would demand more water for compaction. However, the result from the dynamic monitoring test showed that the recycled aggregate was better. It concluded that a combination of concrete waste (75%), asphalt (20%) and ceramic material (5%), would provide a satisfactory load-bearing capacity similar to what a natural aggregate would provide. Some reports have stated that recycled aggregate provides more volume than conversional aggregates for the same weight [8].

The ability of RC to provide the required characteristics necessary for it suitability in pavement construction has being well researched. Depending on the specification for sub-base and base course, different research works have mentioned that it satisfies various specifications and requirements. However, more research into the stress state and permanent strains of RC should be done as asserted by [36]. The durability as well as the aggregate characteristics as regards shrinkage and self-cementing should be examined. Different studies have mentioned that the higher alkali content in RC should be examined. More studies into RC gradation especially fine grains should be done less than 1.18 mm. Also, effects of different pozzolans on RC concrete should be explored.

The next step would be more field trials especially in developing countries. When RC do not meet the specification, stabilization can be carried out to improve the properties of the RC [37], [38]. However, attention must be placed on the resilient modulus due to effects of hydration process.

In any typical asphalt pavement, 4-5% of the structure is bitumen. This bitumen portion can be re-laid every 10 to 20 years depending on it performance. The removal is done with a milling machine, then sorted and batched afterward. RAP can be used as the asphalt layer again as part of the asphalt mixture. Asphalt can be recycled 100% [8][3].
Wastes such as Fly ash FA, Waste lime, Cement kiln dust (CKD), have been explored as fillers for asphalt mixture. Studies have shown that the inclusion of these and fine RC would have negative impact on asphalt mixture instead improving its engineering characteristics. They are effective and economical [39]–[42]. [43] utilized recycled fine aggregates powder as a filler in asphalt mixture. The study revealed that properties such as water sensitivity, high-temperature properties and fatigue resistance were improved on. Conversely, the low temperature performance decreased.
The research of [6] compared the performance of recycled brick powder and limestone stone filler as asphalt filler. The brick powder was obtained by drying washed brick at $80^{O}C$ for 10 hours. After which the brick was grounded using a jaw crusher and ball mill for 15 minutes. The study carried out water sensitivity tests, indirect tensile tests, static and dynamic creep tests and fatigue tests. The tests were carried out in accordance to AASHTO T-283, AASHTO TP31 and AASHTO T-321 respectively. Draindown test according to AASHTO T-305 was performed. The material compared had similar properties. However, the recycled brick powder had higher specific surface area and absorption. The study observed that the asphalt with recycled brick filler had better indirect tensile modulus, decreased permanent deformation at $60^{O}C$ as well as improved fatigue life and water sensitive. More research needs to be carried out, as recycled brick powder would varies from place to place.
For recycled aggregate to be used in asphalt mixes, the moisture content must be low. An increase in the moisture content by 1% would require 10% more fuel per tonne. Consequently, several reports have stated that the reduction of the aggregate moisture content by 2%, would save 8.7 kWh and 2.02 kg CO_2 per ton [3]. There it has to be stored which would increase the cost of operation.
[17] reported that 3,553 kwh per year can be saved if all waste CDW generated were recycled in Thailand. Approximately, about 106 million euros can be saved annually which is a new stream of income for both individual and country. Conversely, [22] reported that recycled aggregates are far more expensive than natural aggregates as illustrated in Fig 8.

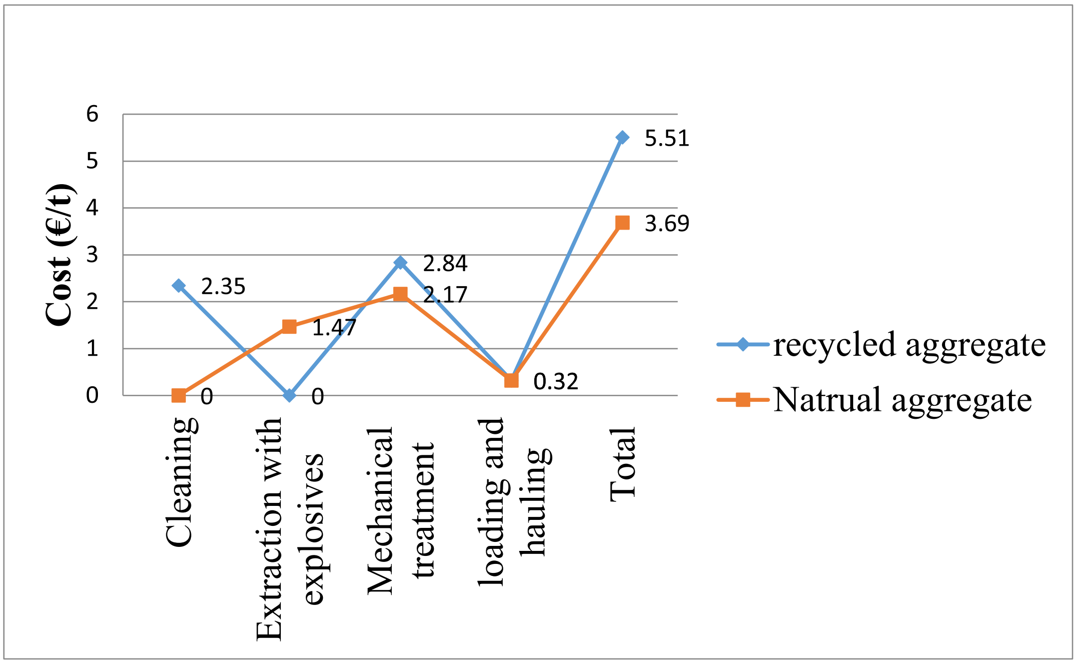

Fig 7: Manufacturing costs of Aggregate

2.3 Environmental and Economic Impact of CDW

The environmental and economic impact of various disposal methods of CDW were evaluated using dynamic model [44]. The study revealed that recycling was the best method. Theoretically, recycling 20% of CDW would reduce the cost of L.E. 112,636.8 billion ($16,161.35 billion) over a 20 year period. It concluded by reinforcing the facts that recycling helps to conserve raw materials and landfills space, reduce GHG emission and costs to mitigate pollution.

[19] stated that recycling of aggregates requires about 4.0 kg CO_2 per tonne, which is 22 to 46% lower than the convention aggregate. The utilization of 50% RC during in road construction would reduce the embodied energy and GHG emission of material component by 23% [45]. The use of RC helps to reduce GHG emission by 65% while saving 58% non-renewable energy consumption [46]. This was also observed by [47] as shown in Table 4.

Table 3: comparative evaluation of CO_2 emissions and the embodied energy of recycled aggregate vs. quarried virgin aggregate [47].

	Comparative CO2 emissions per kilometre in road base construction (tons/kilometre) (approximately)	Comparative embodied energy per kilometre in roadway construction		Total energy impact (Gj/kilometre)
		Embodied energy (Gj/kilometre)	Operational energy (Gj/kilometre)	
Recycled road base (100%)	24	165	186	351

Quarried road base (100%)	72	762	191	953

[48] observed that the use of 50% RCA or RC by volume in the concrete mixture on a 3-lane highways with concrete shoulders would save $2.26 per tonnes of RC (RCA). For the entire project, $5,517 saving without landfilling saving included. The utilization of 100% RCA base course would save $22,658. In addition, the use of RC at 50% in concrete mixture would save $28,172. Factoring the landfilling saving of about $279,280, the total saving is about $307,452 for a 3-lane mile long project. The drawback observed the utilization of the two-stage mixing developed by [49] which increase mixing time from 120 seconds to about 270seconds.
This is every important for developing where lots of new construction or reconstruction would be carried out. The cost of materials alone account for about 60% of the total project cost [50]. The utilization of RC would significantly reduce road infrastructural construction as road transportation is an essential component of national growth [51-54].

3. Conclusion

A huge amount of Natural aggregates of about 40 billion tonnes is extracted annually to meet the global demand necessary to support the expansion of the built environment. Different studies have proven that recycled aggregate can be used to minimize the huge extraction. Consequently, it helps to address landfill space usage, reduce GHG emissions, and create new economic benefits. Waste sorting at source, lack of data, policy development and enforcement coupled with poor waste management with little or no landfill management makes the use of CDW difficult in developing countries. From the review it can be concluded that:

i. Recycled aggregates are not always homogenous.
ii. Resilient modulus of asphalt containing recycled aggregates reduced as binder was added.
iii. Recycled aggregates is suitable for pavement interlayer ranging from CBR tests, permanent deformation properties, resilient response, degree of compaction, gradation, shear resistance and stability.
iv. It concluded that a combination of concrete waste (75%), asphalt (20%) and ceramic material (5%), would provide a satisfactory load-bearing capacity similar to what a natural aggregate would provide.
v. Recycled aggregate provides more volume than conversional aggregates for the same weight.
vi. For recycled aggregate to be used in asphalt mixes, the moisture content must be low.

4. Recommendation

It is recommended that CDW are bulky and not suitable for composting and incineration and hence the re-use of this waste should be enforced. This will reduce the energy cost associated with mining, extraction and transportation of natural aggregates.

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