Alma Mater Studiorum - Università di Bologna

DOTTORATO DI RICERCA IN

SALUTE, SICUREZZA E SISTEMI DEL VERDE

Ciclo 35

Settore Concorsuale: 07/C1 - INGEGNERIA AGRARIA, FORESTALE E DEI BIOSISTEMI

Settore Scientifico Disciplinare: AGR/10 - COSTRUZIONI RURALI E TERRITORIO AGROFORESTALE

SUSTAINABLE PAVEMENTS FOR RURAL SCENARIOS: LABORATORY AND IN-SITU CHARACTERIZATION OF RECYCLED MATERIALS AND INNOVATIVE CONSTRUCTION SOLUTIONS

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Esame finale anno 2023

Alma Mater Studiorum University of Bologna

PhD Program of Health, Safety and Green Systems

Cycle XXXV

Sustainable pavements for rural scenarios: laboratory and in-situ characterization of recycled materials and innovative construction solutions

A thesis submitted in fulfilment of the requirements for the degree of
Doctor of Philosophy

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MAY 2023
ALMA MATER STUDIORUM UNIVERSITÀ DI BOLOGNA
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ACKNOWLEDGEMENTS

I would like to express my deep and sincere gratitude to my supervisor, Professor Cesare Sangiorgi. From beginning to end, his broad knowledge, excellent guidance, endless patience, motivations and encouragements have shaped me into becoming a better researcher. His work ethic as an academic has set a great example to me and therefore, I am grateful for the opportunity given to work with him during my master and PhD.

I would also like to extend my gratitude to my associate supervisor, Professor Daniele Torreggiani and the coordinator of PhD program of Health, Safety and Green systems (SSSV) Professor Patrizia Tassinari for their valuable guidance and advices. The opportunity to be working with experts from other disciplines has been very helpful and eye-opening.

I wish to thank my University, ALMA MATER STUDIORUM Università di Bologna, for giving the chance, admitting and funding my doctorate. Without support, it would be very hard to complete my study.

I am also thankful to my colleagues at Unibo who always made me feel cared for, motivated and excited to work. My dear friend, Dr. Abbas Solouki has made great helping for me from the beginning of my PhD career with some most useful but non-written academic advices and instructions. Also, many other friends such as Dr Piergiorgio Tataranni, Dr Giulia Tarsi, Dr Sergio Copetti Callai, Dr Shahin Eskandarsefat, Dr Navid Ghasemi, Eng. Marco Bruno and Eng. Beatrice De Pascale should be thanked for their great helps and contributions in improving the scientific goals of my research.

Moreover, I would like to express my appreciation to all the technical staff at the Road laboratory of University of Bologna especially Ettore Cappellari and Alessandro Lodi.

Also, I would thank all the Italian companies which supported the field operations related to my research, C.A.R Inerti s.p.a, CTI, Valli Zabban and BOMAG Italia; and especially Dr. Gianluca Minarini the executive technical manager of CAR Inerti company in Imola.

Last but not least, my heartfelt gratitude goes to my beloved parents, Aghdas Tousiani and Hassan Pourkhorshidi, for their continuous love, support and encouragement. They have inspired the values of hard work, patience, faith and respect which have helped me through challenging times. Finally, special thanks to my dear sister Mozhgan and my beloved SAM for always having my back.

ABSTRACT

The growing need for developing transport infrastructure has led to expanding research on advances in road pavement materials. Finding innovative solutions that are sustainable, environmentally friendly and cost-efficient is a priority today. Focusing such efforts on low-traffic and rural roads can contribute with a significant progress in the vital circulatory system of transport for rural and agricultural areas. An important alternative material for pavement construction is recycled aggregates from solid wastes, including waste from civil engineering activities, among them mainly construction and demolition ones. Using such alternative requires the adoption of proper technical methods and assessment procedures especially for low-traffic rural roads applications. In this thesis, a comprehensive literature review on the previous studies on specifications, analysis, testing and case studies of recycled aggregates is made at first; and secondly, it is performed a planned set of laboratory testing procedures aimed to fully characterize and assess the potential in-situ mechanical performance and chemical/environmental impact of the selected recycled material for various layered pavement applications. Furthermore, monitoring the full-scale response of the selected materials in a real field construction site, including the production, laying and compaction operations is done by means of Intelligent Compaction Rollers. Moreover, a novel single-phase solution for the construction of semi-flexible paving layers to be used as alternative material to common concrete and bituminous layers is experimented and introduced, aiming the production and laying of a single-phase laid material instead of a traditional two phases grouted macadam. Finally, on a parallel research work for farming pavements, the possible use of common geotechnical anti-erosive products (geocells and geotextiles) for the improvement of soil bearing capacity of paddock areas in cattle husbandries of bio-farms is evaluated. On the whole, this thesis has clearly demonstrated the feasibility of using the sustainable recycled aggregates for low-traffic rural roads and the pavements of farming and agriculture areas. It is also shown that the application to the construction of rural roads is compatible with the existing technologies. The materials exhibit satisfying characteristics in laboratory assessments, including fragmentation and post-compaction stiffness, which permits considering them for further field evaluations. The pavement layers constructed with recycled aggregates provided satisfying performance under heavy traffic conditions and weathering in single or double layered experimental pavements. This, together with the fact that these aggregates can be available in most areas and in large quantities, provides a great impetus towards shifting from traditional materials to more sustainable alternatives. Other than considerable load-bearing performance, the chemical and environmental stability of these materials based on the leaching measurements, proves their soundness to be utilized in natural and farming environments.

ASTRATTO

La crescente necessità di sviluppare infrastrutture di trasporto ha portato ad ampliare la ricerca verso lo sviluppo di materiali innovativi per la pavimentazione stradale. Trovare soluzioni innovative che siano sostenibili, rispettose dell'ambiente ed efficienti in termini di costi è oggi una priorità. Concentrare tali sforzi sulle strade a basso traffico e rurali può contribuire ad uno sviluppo significativo nel sistema dei trasporti per le aree rurali e agricole. Un importante materiale alternativo per la costruzione di pavimentazioni è l'aggregato riciclato da rifiuti solidi, compresi i rifiuti provenienti da attività di ingegneria civile, tra cui principalmente quelle di costruzione e demolizione. L'utilizzo di tale materiale alternativo richiede l'adozione di metodi tecnici e procedure di valutazione adeguati, in particolare per le applicazioni su strade rurali a basso traffico. In questa tesi, viene inizialmente effettuata una revisione completa della letteratura sugli studi precedentemente svolti su specifiche, analisi, test e casi di studio di aggregati riciclati. In secondo luogo, viene eseguita una serie pianificata di test di laboratorio volte a caratterizzare e valutare le potenziali prestazioni meccaniche in situ e l'impatto chimico/ambientale del materiale riciclato selezionato per varie applicazioni in diversi strati della pavimentazione. Inoltre, il monitoraggio della risposta su vasta scala dei materiali selezionati in un cantiere reale, comprese le operazioni di produzione, posa e compattazione, è stato effettuato mediante rulli di compattazione intelligenti. È stata poi sperimentata e introdotta una nuova soluzione monofase per la realizzazione di manti semi-flessibili da utilizzare come materiale alternativo ai comuni manti cementizi e bituminosi, finalizzata alla produzione e alla posa in opera di un materiale prodotto in un'unica fase, invece di un tradizionale macadam stuccato in due fasi. Infine, in parallelo al lavoro di ricerca per le pavimentazioni agricole, viene valutato il possibile utilizzo di comuni prodotti geotecnici anti erosivi (geo-celle e geotessili) per il miglioramento della portanza del suolo delle aree a paddock negli allevamenti bovini delle bio-aziende. Nel complesso, questa tesi ha chiaramente dimostrato la fattibilità dell'utilizzo di aggregati riciclati sostenibili per strade rurali a basso traffico e pavimentazioni di aree agricole. Si dimostra inoltre che le fasi esecutive della costruzione di strade rurali sono compatibile con le tecnologie esistenti. I materiali presentano caratteristiche soddisfacenti nelle valutazioni di laboratorio, inclusa la frammentazione e la rigidità post-compattazione, che consente di considerarli per ulteriori valutazioni sul campo. Gli strati di pavimentazione realizzati con inerti riciclati hanno fornito prestazioni soddisfacenti in condizioni di traffico intenso e di agenti atmosferici sia in pavimentazioni sperimentali a strato singolo che doppio. Questo, insieme al fatto che questi aggregati possono essere disponibili nella maggior parte delle aree e in grandi quantità, fornisce un grade risultato per incentivare il passaggio dai materiali tradizionali ad alternative più sostenibili. Oltre alle notevoli prestazioni portanti, la stabilità chimica e ambientale di questi materiali, sulla base delle misure di lisciviazione, ne dimostra la validità per l'utilizzo in ambienti naturali e agricoli.

CONTENTS

KEYWORDS

Sustainable Roads

Rural and Farming Pavements

Recycled Aggregates

Construction and Demolition Waste

Continuous Compaction Control

Husbandry Paddocks

ABBREVIATIONS

ASFC	Stabilized mix of reclaimed asphalt and crushed concrete *(Asfalto-Cemento*)
CBR	California Bearing Ratio
CCC	Continuous Compaction Control
CDW	Construction and Demolition Waste
CV	Coefficient of Variation
DI	De-ionized
DSLT	Horizontal Dynamic Surface Leaching Tests
Dyn. CBR	Dynamic California Bearing Ratio
EC	Electric Conductivity
EC-CPR	European Commission Construction Products Regulation
Gt	Giga tones
HMA	Hot Mix Asphalt
ITS	Indirect Tensile Strength
ITSM	Indirect Tensile Stiffness Modulus
ITSR	Indirect Tensile Strength Ratio
L/S	Liquid to Solid ratio
LWD	Lightweight Deflectometer
MDD	Maximum Dry Density
MTRV	Mix of Crushed concrete sleepers and industrial foundry waste *(Misto Traversine)*
OMC	Optimum Moisture Content
PLT	Plate Load Test
RAP	Reclaimed Asphalt
RCA	Recycled Concrete Aggregate
STRV	Stabilized crushed concrete sleepers aggregates *(Stabilizzato di Traversine)*
WMA	Warm Mix Asphalt

CHAPTER 1: INTRODUCTION

BACKGROUND

Well-functioning and low impacting mobility infrastructures are keystones for modern and sustainable societies. Infrastructures have an important role in contributing to business transitions, and they increase a country's economic efficiency, enhancing the standard of living of its citizens. As such, there is a positive correlation between the gross domestic product of countries and their infrastructure quality with the two of them sharing a cyclical relationship. Economic growth allows for additional infrastructural investments, while infrastructure is a necessary component in improving economic conditions. Indeed, the considerable match and correlation of countries' economic power and their development of infrastructures has been proven by many recent published statistics [1](Figure 1).

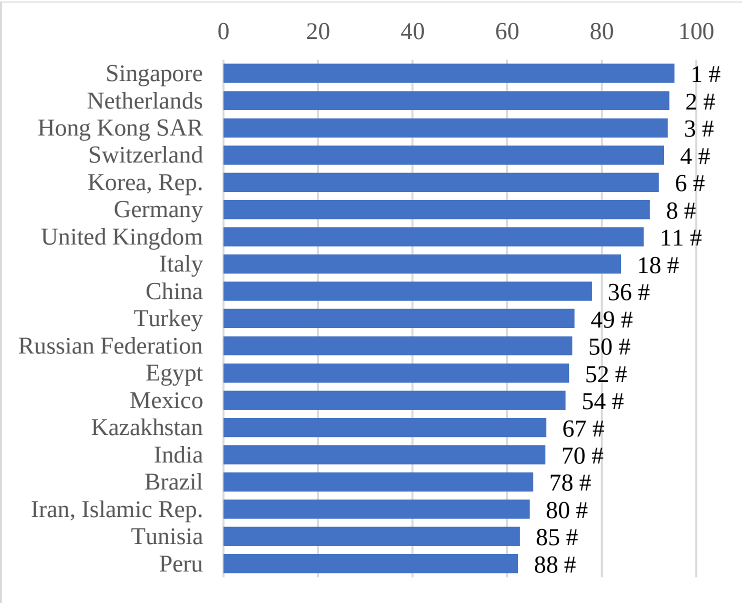

Figure 1. Ranking of some selected countries according to the infrastructure quality index in 2019 [1].

Transport, energy, communications, water, waste and defence are all examples of sectors requiring developed infrastructures in order to operate effectively and efficiently. Transport infrastructure is typically the most discussed form of infrastructure and a primary focus of resources, in part because it has a direct effect on the lives of citizens that is both tangible and visible. Transportation infrastructures, and roads in particular, are one of the main keys of development and progress in every country. Being directly linked to the supply of goods and transport of products and passengers, they have a major role in economic turnover and life quality of countries.

Developing the infrastructures of transportation has become one of the essential tasks of governments, authorities and public sectors; and it takes billions of dollars for their construction, operate and maintenance each year. Other than continuous expenditures, they have other challenges including the use of large amounts of construction materials, the requirement of well-recognized technical methods, assessment procedures and, last but not least, a potential environmental burden due to their construction and service life externalities. Each of these aspects have been targeted by a very large amount of researches and investigations performed all over the world, all of them aiming to improve the quality, efficiency and reliability of these infrastructures.

Roads are the main element of the basic transportation infrastructure, which allow traffic flows and mobility in all its forms. Roads usually consist of a vast network of highways, main roads, low-traffic and rural roads that connect residential, industrial and agricultural areas to each other. Road networks in most countries therefore reflect the development of a hierarchy of roads, with motorways at the highest level and local access roads at the lowest. It is important that the hierarchy is clarified to cope with guidelines that link design to function, throughout the network. Constructing the roads demands a series of technical instructions, testing methods, standards and procedures generated from engineering design approaches linked to scientific knowledge, results of researches, modelling, and other scientific investigations performed in the laboratories and often in full scale trial sites.

In this context; rural, low-traffic and farm roads, in many countries form the essential circulatory system of transport for rural and agricultural termini, which usually has a considerable role in the supply chain reliability of agricultural and farm products. They are often considered as an entry point for poverty alleviation and employment generation. The overall length of these roads can be much more than highway and major roads. As an example, in U.S. in 2020, despite only 19% of population lived in rural areas, 68% of the country total road length was accounted for rural roads [2]. Also in India, Rural roads constituted 71.4 percent of the total road network in 2019 [3]. Besides, roads are also of high relevance for farm and agricultural areas, as the farming has moved toward becoming more mechanized in recent decades. Large farming and agriculture machinery and vehicles demand special attention to construction of these low traffic -but heavy loaded- roads and pavements.

One of the main subjects of constructing the road network and the connected paved surfaces, is pavement engineering. In general, from the pavement point of view, roads are usually divided into two categories: bituminous (flexible) and concrete (rigid) pavements. Both types of roads are layered systems, encompassing at least a foundation and a base or sub-base layer; these are designed based on various parameters including traffic volume and load, weather condition, available materials, existing subgrade, etc. Each of the road's challenges mentioned above are mainly answered in pavement engineering. These challenges would have different solutions based on different conditions, which demand vast technical, scientific and model-based assessments to resolve. The three mentioned challenges are:

1- **Providing the necessary construction materials:** The initial and essential need for constructing pavements, is the availability of materials. Huge amounts of raw and recycled materials are exploited for providing the basic supply for the construction of roads. As a statistical example, in Europe, a total amount of 280 million tons of aggregates have been used for hot and cold mix asphalts in 2020, which reached up to the 370 million tons in U.S in the same year [4]. The amount of required material for constructing each square meter of road pavements depends on many technical aspects such as their design, thickness, type of aggregates, binders and targeted levels of compaction. The complexity and diversity of pavements makes it hard to provide a preliminary estimation on the average tonnage of materials needed for the construction of roads. It goes without saying that the pavement sector is one (and maybe the first) of the high raw-material consuming industries of the modern world. This highlights the importance of studies on the use of sustainable materials for pavements.

2- **Applying the proper technical methods and assessment procedures:** Utilizing the provided materials for constructing the pavements need very detailed engineering design, precise technical instructions and assessment procedures. The design is the most important task as it requires full knowledge of the possible climatic exposure of the pavement, the amount and type of traffic and the available construction materials (such as aggregates and binders). In fact, the pavement engineers should complete the design process based on the materials characteristics and final roads assessment criteria, which requires sufficient knowledge of pavement design, construction and quality control methods.

3- **Dealing with the environmental concerns due to the possible externalities:** This last issue has raised in recent decades as the environmental effects of human activities including road and structural construction started to be evidently acting on the ecological stability of planet earth. Together with many other sectors such as energy, industry and transport, road construction activities have a major role in the irreversible changes on the climate and exploitation of natural resources. Other than these, the effect of road infrastructures on the hosting natural territories such as forests and habitats of sensitive species must be considered, along with the potential chemical pollutions and soil contaminations originated from the materials used for pavements construction and maintenance.

It is an established maxim that effective transportation plays a crucial role in rural socio-economic development and in reducing poverty. The typical scenario in most low-income countries is of a large rural population with agricultural-based economies where the main imperative is to provide rural communities with safe and efficient access to basic services. In these countries, a high percentage of the rural road network is unpaved and conventional road-building materials are often scarce or available only at high cost [5]. One of the most important issues in rural, low-traffic and farm roads other than their territorial distribution and main network connection, is their pavement design and material demands. These aspects, together with the fact that usually public road infrastructures use the public budget for the construction, monitoring and maintenance phases, highlight the importance of specific design approaches and material assessment methods to be applied on a vast network of roads (Figure 2). Moreover, some rural pavements may possibly need special design refinements due to their featured use, such as the trafficking of super heavy agricultural machinery and vehicles, and the limits for soil contamination, especially in agricultural environments. These facts, elevates the importance of upgrading of scientific and technical specifications of traditional methods, procedures and technologies to be adopted by alternative materials, road construction machinery and technologies together with contemporary environmental concerns.

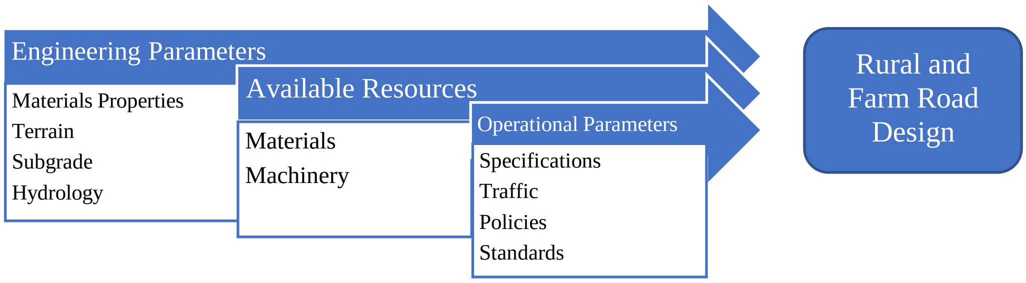

Figure 2. The main design factors of rural roads [5].

The functional definition of farm road is the road that links farmland areas or villages to collector roads to enable transportation of inputs to farms and agriculture products to markets. However, farm roads are mainly defined as low volume traffic roads, usually without asphaltic or concrete surfacing. Other than constructing roads, pavement engineering could have many other applications related to farms and agriculture. The geotechnical knowledge of pavement engineering can be applied to various agriculture complexes, including animal husbandries, to improve the quality, durability and other engineering aspects of many paved or surface-treated areas. The benefits of adopting these methods for a number of farming applications - farm roads, animal-house floors and bases for some storage areas - have become increasingly recognized over the years. In the headings that follow, the main areas of use are considered:

Farm roads: farm roads have been constructed in a not-designed fashion over a long period of time from hardcore, gravel or crushed stone, or even simply compacted soil. Whilst this form of construction gave adequate performance under light farm vehicles and pedestrian use, it is often inadequate to resist the high stresses of modern heavy delivery/collection lorries and other wheeled machinery, resulting in an increasing need for regular maintenance of potholes and damaged areas. Potholes left unattended not only present a safety hazard, but they are also likely to give rise to increased costs of maintenance of farm vehicles bumping over them. Also, where delicate products such as fruit and vegetables, are being transported, a potholed road can damage the produce and thus reduce the income [6]. These problems highlight some of the benefits of a paved farm road, which can provide a low- maintenance, durable and even surface finish. In addition, this type of road can be constructed in stages, with the final surface course being applied, if necessary, a year or more after the lower layers, thus helping to spread construction costs.

One drawback related to rural roads could be the fact that to obtain the best performance from their paving, they should be laid using specialized plant and labour, and therefore only experienced surfacing professionals are to be employed. Moreover, the good long-term durability of the surfacings can be reduced by abnormal mechanical abrasion and point loadings and also by allowing agriculture and faming contaminants on the surface. Where such conditions prevail stronger, denser and stiffer layers will provide a better resistance, but where heavy loads by tracked vehicles, spade-lugged or cleated wheels or sharp/scraping farm implements are likely to transit or where accumulations of farming contaminants are unavoidable, special pavements or alternative forms of construction (e.g. concrete) will be advisable [7].

Farm yards: Yards on farms are used for a wide range of purposes, from very light use, such as car parking, to very heavy or aggressive use, for storage of heavy mechanical plant or as paved areas for livestock. As indicated in the above notes on farm roads, the durability of pavements can be affected by mechanical damage and heavy point loadings and by accumulations of contaminants such as mud and animal droppings. The surface materials can also be damaged by possible spillages of petroleum oils such as diesel and lubricating oil (e.g. spillages at fuel storage/refuelling points or vehicle maintenance areas), which imposes special technical design considerations**.**

Animal-house floors: The main use of paving in the surfacing of animal house floors has been on cow cubicle beds, on which there has been growing use of the materials over the recent years. Advantages claimed for these surfacings in this application include: reduced usage of bedding material; increased animal comfort as a result of good insulation; increased floor durability; improved hygiene; good slip-resistance; ease of maintenance. Retention of urine on the surfacing could be one of the main problems which should be prevented by precise design and construction of surface gradient, drainage and cleaning systems**.**

Storage bases: A fairly recent development in the use of modern pavements on farms has been in the construction of bases for silage storage. This development has arisen as a result of the poor durability of traditional forms of construction due to the aggressive nature of some of the fermentation products from silage. Any solution should have reasonable resistance to many chemicals, appear to offer increased durability in these applications [7].

Other: One of the possible applications of pavement and geotechnical engineering is in reinforcing paddock and foraging areas. Usually paddocks are open areas where animals walk on during the dry seasons. In fact, the formed mud in wet seasons can be a problem for animals’ safety and health, which could be solved by many reinforcement solutions conceived for engineering applications.

Large amount of employed materials for constructing roads and pavements means large exploitation of natural resources for supplying them where needed. The increasing rate of development all over the world by emerging new economic powers and developing countries, imposes the necessity of providing higher and higher amounts of aggregates, binders and other main raw components needed for expanding the transportation infrastructures. As an example, the total extracted amount of non-metallic minerals (which include the aggregates needed for civil engineering activities) and total amount of materials in stock in the 20th century until 2015 is demonstrated among other categories in Figure 3, which proves the huge amount of extraction and piling of aggregates due to the infrastructure development all over the world. In 2015, the total amount of extracted natural aggregate all over the world reached to the amount of 6Gt/year [8] which demonstrates an enormous accelerating irreversible effect of civil engineering activities on the planet earth. As the modelling and prediction scenario done by Krausmann et al. demonstrated in Figure 3, the extraction of minerals will continue to speed up to catastrophic volumes until 2050. This draws attention to the importance of the application of more sustainable alternatives to traditional natural aggregates and materials for construction, including the road and pavement structure. Numerous academic researches and case study investigations have been done on the possible substitution of traditional natural aggregates with recycled ones, which were mainly encouraged by the authorities of countries where saving natural resources and environmental concerns are today among the most critical topics for decision makers.

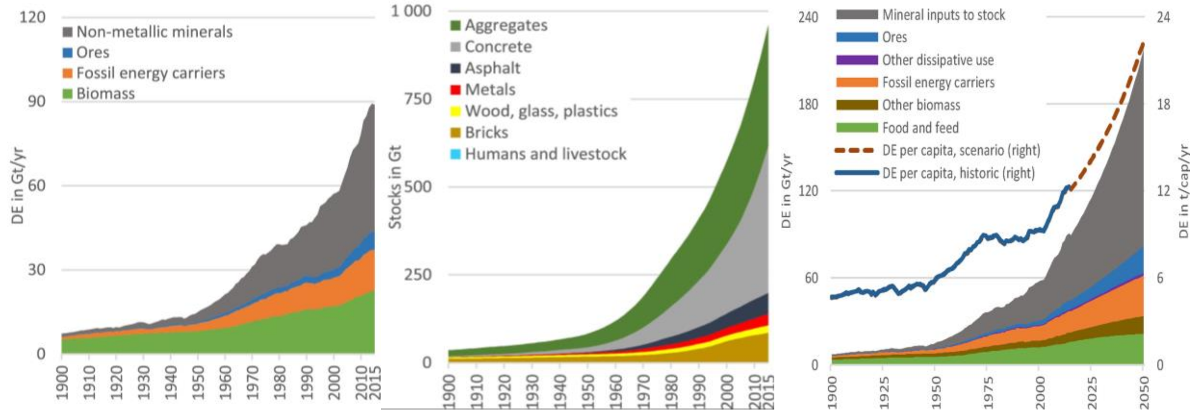

Figure 3. Global material flows in Gt/year and stocks in Gt from 1900 to 2015. Left: material extraction by main material group. Middle: stocks of various categories of capital in Gt. Right: Global convergence scenario of global material extraction in Gt/year by main material groups (left axis) and in t/cap/year (right axis) [8].

One of the main categories of the sustainable materials for infrastructures and pavements, are aggregates recycled from the construction and demolition wastes of different civil engineering activities. Demolition of old road pavements (Reclaimed asphalt pavement- RAP), construction and demolition of buildings (construction and demolition- CDW), demolition of structural or non-structural concrete (Recycled Concrete Aggregates-RCA), etc. produce huge amounts of waste, which have been often disposed in landfills. Recycling these materials into usable aggregates for construction can have a great contribution towards saving natural resources, which is an ongoing sustainable trend in many developed countries. The environmental agencies of the different regional governments are mainly responsible for regulating the use of secondary materials in road building and other construction applications. This means that ongoing researches and investigations should be performed in order to generate the regulations, standards and technical knowledge for the safe use of these alternative aggregates.

Considering that pavements are one of the principal elements of road infrastructures, in recent years a large number of researches and investigations have been encouraged on the use of sustainable - and mainly recycled - materials for pavements. On the light of the wide existing literature, the main problems arisen for the employment of recycled aggregates for road infrastructures and other paved areas are:

- **Variety of sources:** A wide variety of waste origin can be the source of recycled aggregates. As an example, recycled concrete aggregates (RCA) can have highly scattered properties due to the type of cement, nature and grading of virgin aggregates, the hydration and the weathering during concrete service, etc. This makes the design and editing of specifications more difficult, as it looks like every application of recycled aggregates should be preceded by a comprehensive series of laboratory and field technical assessments on them.
- **Delivering in mixed blends:** In some cases, the separation of various categories of recycled aggregates are not possible due to the underwent plant treatment processes, hence the recycled aggregates usually become delivered in their original mixed state. The mixes of gravel and reclaimed asphalt originated from demolition of roads and other paved bituminous areas, or the mix of crushed masonry, tiles and concrete aggregates in CDW is very common. This mixed nature, if not under control, can be sometimes detrimental for the main mechanical and chemical characteristics of the blend. Weaker or polluting particles can actually limit the applicability of recycled aggregates in the construction of pavements.
- **Range of applications:** The variety of applications of recycled aggregates in infrastructure, makes the study of these materials more complicated. This means that each sets of sources, physical and technical properties of studied materials, should be re-evaluated based on the different applications and diverse service circumstances. As an example, the use of any recycled aggregates in base layers of high traffic urban roads is different from its application in the surface layer of rural roads with low traffic, but heavy axle loads. Besides, the construction methods for each case differs from project to project, and the design and control specifications should be taken into account together with the materials properties in order to provide the most reliable project specs.

AIMS AND OBJECTIVES

In the light of the emerging targets for sustainability of the pavements' construction sector, the extended applicability of fully recycled materials and green/durable construction solutions for rural roads and farming pavements are the main driving objectives of this research work. In particular, they aim to assess the possible use of recycled aggregates from construction and demolition waste sources to be applied in simple and easy to maintain paving solutions for low volume rural roads, other minor pavements in farming facilities and similar non-urban contexts, where the risk of environmental impact is higher. The application of the reliable quality control approaches for compacted layers is also proposed along with the use of a geo-cells sandwich reinforcing solution for husbandry paddocks.

To achieve the above targets, the following corresponding sub-objectives were set:

1. Completing a comprehensive literature review on the existing documents (scientific papers, technical reports, guidelines and case histories) on specifications, analysis, testing and case studies of recycled aggregates from waste of different civil engineering activities and demolition of various structures including pavements. Additionally, the use of one of the main groups of waste materials – the agricultural residual bio-wastes- has been considered to study, to widen the range of recycled materials that are available in agro-societies and developing countries.
2. Identifying the possible common and novel sources of CDW materials to be fully characterized and adopted for the design of one, two- or three-layered pavements for the above-mentioned applications. These include full RAP mixtures and high-strength recycled concrete aggregate mixes from railway sleepers.
3. Performing a well-defined set of laboratory testing procedures aimed to fully characterize and assess the potential in-situ performance of the nominated recycled material for various layered pavement applications.
4. Monitoring the full-scale response of the selected materials in a real field construction site, including the production, laying and compaction operations completed by means of Intelligent Compaction Rollers. The consecutive (in time and space) construction of layers allows the evaluation of the materials in one (unbound) or multi-layered (bound and unbound) pavements.
5. Experimenting a novel single-phase solution for the construction of semi-flexible paving layers to be used as alternative material to common reinforced cement concrete layers and bituminous layers. In this work, the application aims at the production and laying of a single-phase laid material instead of a traditional two phases grouted macadam.
6. Assessing the chemical characteristics of the selected materials with respect of their main constituents and measuring their leaching potential for the possible application in permeable pavements of countryside, farming and agricultural contexts.
7. Evaluate the possible use of common geotechnical anti-erosive products (geocells and geotextiles) for the improvement of soil bearing capacity of paddock areas in cattle husbandries of bio-farms, aiming at the extension of the external season and to the increase of animals' safety and health.

THE NOVELTY AND SIGNIFICANCE OF THE RESEARCH

Numerous researches have been previously completed on the use of construction and demolition waste recycled aggregates for roads and other surface pavements, however in the present work, some new perspectives and applications of their recycling are proposed in a laboratory and trial site assessment comprehensive study. Below are some key aspects related to the originality of the research:

1. The characteristics of the selected recycled aggregates were assessed not only as single constituents, but also when used in blends with other types of recycled aggregates. This allowed to quantify the possible interactions between different types of aggregates with diverse properties in laboratory tests and real field construction works.
2. The latest intelligent approaches to compaction of pavement layers were applied by means of Continuous Compaction Control (CCC) rollers in the experimental trial site. This made it possible to compare the vibratory response of different materials during and after compaction. A threshold criterion for the bearing capacity of the layers has been also introduced for different kinds of materials in the multi-layered experimental pavement.
3. The selected recycled aggregates were mechanically tested and chemically evaluated for their possible application in all the main pavement layers of the test road section. In many completed researches, the properties of these kind of aggregates have been mainly assessed for their use in specific individual layers, and a targeted research on the possible use of the same recycled aggregates in different blends of different layers (including cemented ones) was missing.
4. One of the most durable and high-quality type of semi-flexible pavements (grouted macadams) was conceived in an innovative, faster and more sustainable single phase, cold produced and cold laid way. The effectiveness of the proposed solution, compared to the traditional one, was laboratory assessed and proven feasible.

STRUCTURE OF THESIS

The different steps and the relations of different parts of this PhD project is demonstrated in structural chart of Figure 4. The thesis background, objectives, experiments and results are reported in 7 connected chapters, as listed below:

Chapter 2: This chapter contains two parts describing the comprehensive literature review on recent researches related to recycled aggregates, summarizing the current knowledge on the common alternative aggregates obtained from construction and demolition wastes and agriculture residues to be used in pavements. The references related to recycled aggregates of CDW are mainly focused on laboratory evaluations of these materials; however, some case studies that are related to the topic of the thesis are also reviewed and reported. In the second part, the researches related to the use of agriculture residue waste materials in pavements are described.

Chapter 3: The results and analysis of the laboratory testing on the selected recycled aggregates are discussed in this chapter. It includes the experimental work done on the assessment of the physical and mechanical properties of single and combined batches of recycled aggregates from construction and demolition wastes from different sources. Results corresponding to the suitable mix combinations and optimum percentage were highlighted. Hence, this chapter answered the third objective of this research.

Chapter 4: The results of the full-scale trial site constructed with mixes of recycled aggregates are presented in this chapter. Two consecutive analysis related to the production, laying and compaction of the two main layers of foundation and base layer of the test road section where assessed and subject to real traffic of heavy axle load trucks. The data from laboratory test results were benefitted to analyse the compaction behaviour of various blends of recycled materials. The operational limitations and criteria, together with the correlation of two sets of data collected by spot tests and compacting rollers are presented.

Chapter 5: An innovative single-phase mixing-and-laying method of recycled materials for a semi-flexible surface layer is introduced in this chapter. The basic characterization of the constituent materials, the optimization of their volumetric composition and the identification of the best compromise in terms of mechanical and volumetric properties have been assessed and is here reported.

Chapter 6: The use of recognized geotechnical methods for the reinforcement of lower pavement layers of roads is here proposed to improve the mechanical surface characteristics of a real cattle paddock soil with respect to the possible seasonal alterations due to rainfalls. This includes the construction of a geocells sandwich containing crushed aggregates under a thin layer of top soil, and the evaluation of the bearing capacity of the reinforced pavement against a non-reinforced section.

Chapter 7: The conclusions of the overall findings from this research, as well as the list of feasible recommendations for future work are presented in this chapter.

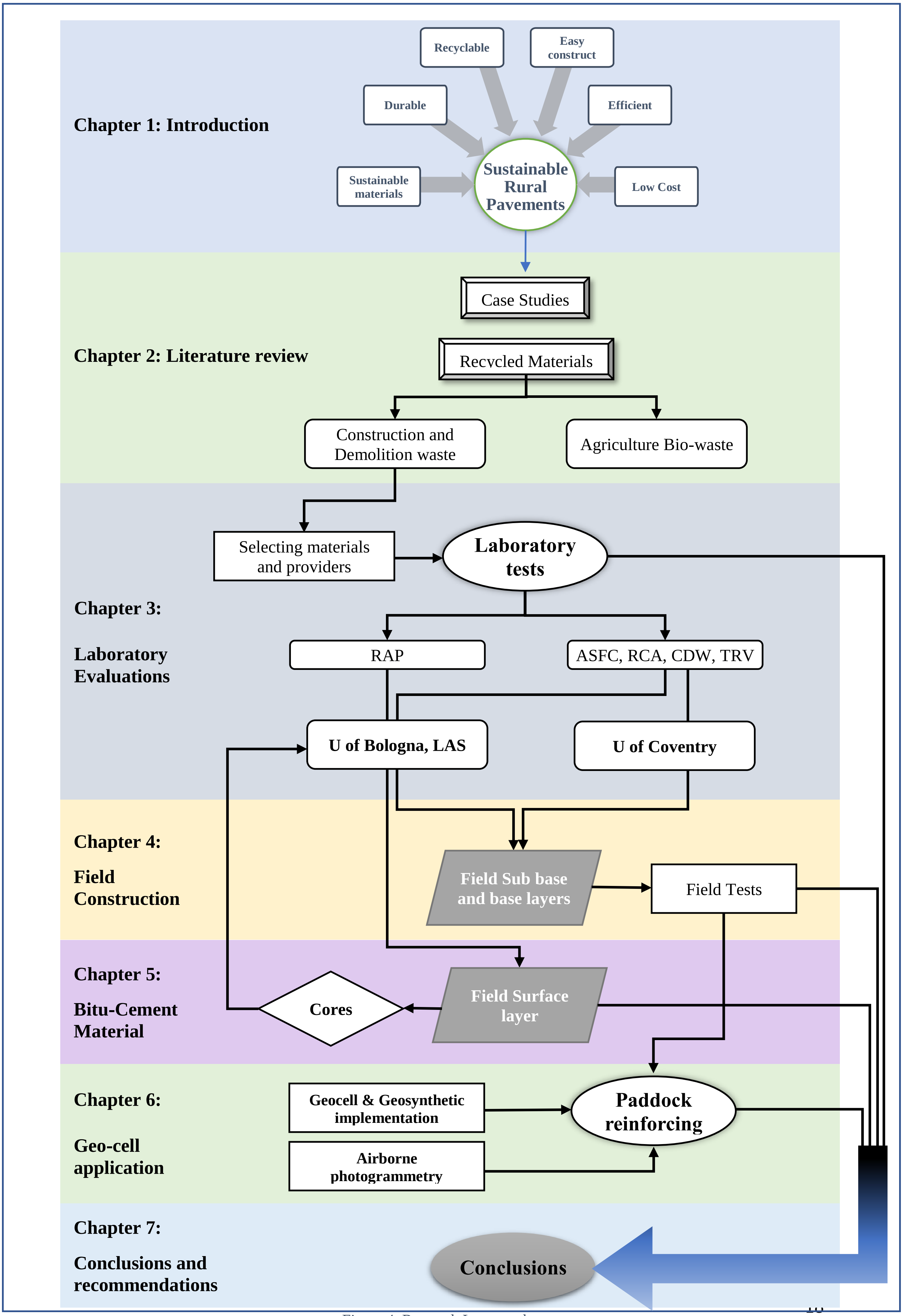

Figure 4. Research Layout scheme.

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CHAPTER 2: REVIEWS ON DIFFERENT TYPES OF RECYCLED MATERIALS FOR RURAL PAVEMENTS AND OTHER MINOR PAVING APPLICATIONS

FOREWORD:

In this chapter, a review on the most recent researches done on laboratory tests and in-situ evaluations of recycled materials to be used in rural road layers and other minor paving applications is done based on the selection of literature by the sources of the materials. In part one, the researches related to the aggregates obtained from construction and demolition wastes are reviewed, while part two discusses the recycled bio-wastes obtained from residues of agriculture and farm activities, which have been experimented in pavement engineering. The distinction the two topics is because they are mainly related to two different group of countries. While construction and demolition wastes are one of the main solid wastes generated in more developed countries, the agricultural economies of many poor, developing and third world countries face the challenge of dealing with large amounts of agriculture residues and wastes. For both the above issues and in a sustainable approach, researchers are in quest of solutions that make use of waste materials for the infrastructure construction and maintenance sector, which usually consumes the highest amounts of raw extracted materials. Other than strategic issue of supplying necessary materials for infrastructure development, environmental concerns of many developed countries including European government, intensively pushes the studies on advancing the "zero-raw, zero-waste" policies. This should be applied also to rural low-traffic roads and to farming facilities and makes the local road administrations and environmental authorities encourage the investigations on the use of more sustainable materials in pavements, possibly reducing the use of virgin ones.

The work presented in this chapter has been published in the following review papers:

1- **Pourkhorshidi, S.**, Sangiorgi, C., Torreggiani, D., Tassinari, P.: Using Recycled Aggregates from Construction and Demolition Waste in Unbound Layers of Pavements, Sustainability. 12, 9386 (2020).

Authorship declaration

A summary of each author's contribution to this work is provided below.

Conceptualization:	S. Pourkhorshidi, C. Sangiorgi
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Writing – review and editing:	C. Sangiorgi
Writing – final editing:	S. Pourkhorshidi, C. Sangiorgi
Supervision:	P. Tassinari, D. Torreggiani

2- **Pourkhorshidi, S.**, Sangiorgi, C., Torreggiani, D., Tassinari, P.: A review of studies on laboratory evaluations of agricultural waste materials for rural and low traffic pavements, International Journal of Environmental Science and Technology (under review), 2023.

Authorship declaration

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sustainability

MDPI

Review

Using Recycled Aggregates from Construction and Demolition Waste in Unbound Layers of Pavements

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Received: 29 September 2020; Accepted: 5 November 2020; Published: 11 November 2020

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Abstract: Pavements are an expensive part of transportation infrastructures, as their construction and maintenance require large amounts of resources and materials every year and all over the world. A sustainable solution for considering environmental concerns about roads and pavements, in general, is utilizing recycled materials for their construction. This has been shown to lower the carbon footprint of the construction sector and to result in natural resource conservation, in reduction of harmful emissions and in minimization of overall costs for pavement construction and maintenance. One of the main groups of recycled materials which has attracted much attention since the end of the last century is construction and demolition waste aggregates (CDW). This paper reviews the completed studies referring to the use of the construction and demolition waste aggregates in unbound layers of pavements and compare the in-hand results from various engineering assessments of these aggregates and mixes. A number of tests and evaluations are applied in order to enhance the required quality and durability of the pavements under given traffic volumes traffic loads and climate actions. Today, unbound recycled aggregates (RA) are mainly used in the lower layers, such as subgrade, capping, sub-base and base, but in rural roads they can be adopted also for bound layers, towards the surface of the structure and may be constituents of bound layers and of novel surfacing applications.

Keywords: recycled materials; construction and demolition; pavements; sustainability; waste

1. Introduction

As traffic capacities and trucks axle weights continue to increase with growing population and development of countries, road construction and its maintenance is becoming more and more frequent all over the world. As road construction activities become more common, the need for construction materials becomes urgent [1,2]. Aggregates undertake more than 90%wt of asphalt mixtures [3] and 100% of unbound layers. Thus, the construction of road infrastructures consumes millions of tons of materials each year, in particular of aggregates (crushed or natural). supplying these amounts would have a detrimental effect on nature and the environment [4]. The old materials used for the construction sites are usually landfilled and new materials are obtained for the purpose of new constructions [1].

On the other hand, even more so today when short chains for goods are desirable, in rural and sub-urban areas, agriculture plays an increasingly crucial and multifunctional role which requires careful design, not only of rural roads but also of the outdoor open working areas of farms. The sustainability of the solutions adopted for these low traffic pavements should become a central pivot of the corporate and territorial strategies in rural areas. These pavements must respond to a variety of requirements and properties, which make them a topic under increasing study and development.

As an example, the agritourism activities and direct on-farm sale of agricultural products bring attention to the development of low-impact solutions, which combine the obvious structural and functional requirements with the environmental and landscape protection ones. Even in the design of road infrastructures in protected areas, these aspects of environmental and landscape compatibility are of high importance. The same theme is proposed for the construction of paved areas in urban and sub-urban parks or for urban surfaces where recreational activities are foreseen.

Consistent data on the quarried sand, gravel and crushed stone for production of natural aggregates adopted for construction are only available for a limited number of developed countries and for recent years. No data about the extraction of construction minerals in whole world could be found. In various studies, different methods are explained to estimate the quantities of bulk materials employed in construction. For this purpose, data on bitumen production used to indirectly extrapolate the volume of aggregates used for asphalt pavement production, assuming a weight ratio of 1:20. It has also been estimated that the overall material extraction during this century has increased by a factor of 8. For instance, in 2005, roughly 59 giga tons of materials were extracted and used worldwide. The largest increase during this period can be observed for construction minerals, which grew by a factor of 34. Subjected for only 15% of total construction minerals at the beginning of the XXth century, its portion increased sharply after World War II to more than 60% at the beginning of the 70s and reached 74% in 2005 (Figure 1). After World War II, 8% of all construction materials were estimated for sand and gravel used for the production of asphalt. This part enlarged to 14% in 1973 and since then it keep on between 10 and 15% [5].

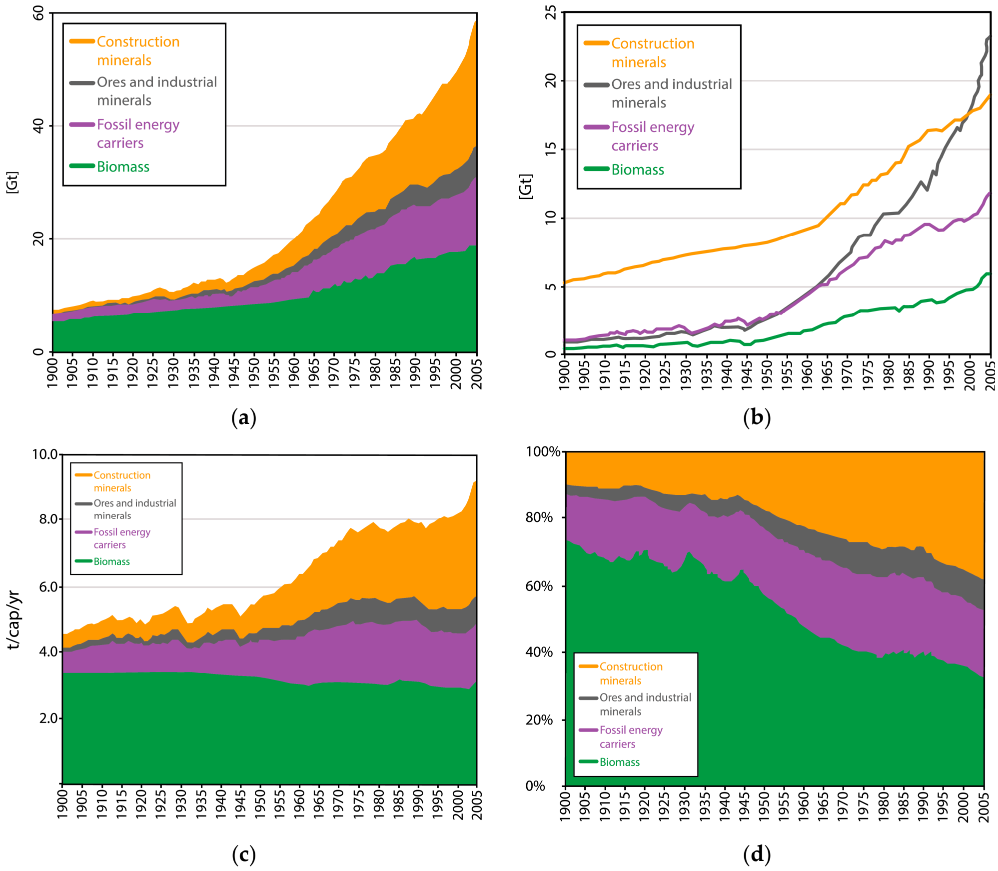

Figure 1. Materials use (on the basis of total quantity of resources extracted equals total quantity of resources used), by material types in the years 1900 to 2005. (**a**,**b**) total materials use in Giga tons (Gt) per year; (**c**) metabolic rate (materials use in t/cap/year); (**d**) share of material types of total materials use [5].

In the light of the above, it is more and more important to find alternative solutions for the supply of construction materials. Besides natural aggregates, the use of recycled materials is today growing in quality and quantities, so that most of the construction projects encompass some sustainable approaches to recycling.

Construction and demolition (CD) activities generated 1.13 billion tones in China in year 2014; and over 530 million tones in United States (US). Construction activities in Europe is the largest producer of waste when compared with other industrial areas, responsible for 35% of the total waste generation which is 2 and 4 times more than the overall household waste produced respectively in US and Europe. European union overall has achieved the horizon of recovery for the year 2020, including backfilling. However, there are still eleven member countries -out of the 19- which need to improve their recovery performance for achieving the EU target [6]. The total production of construction and demolition waste in 28 countries of the European union plus Britain reached more than 368 million tons in the year 2018 [7]. Aggregates from construction and demolition waste (C&DW or simply CDW) can indeed increasingly contribute to the global economy, while relieving utilization of natural resources and satisfying the desired material requirement in different projects. A great potential related to recycling exist, which can be activated by employing proper management approaches and introducing state-of-the-art technologies that can allow C&D wastes to be recycled according to their quality and use [8]. Article 11.2 of the Waste Framework Directive (2008/98/EC) specifies that "Member States shall take the necessary measures designed to achieve that by 2020 a minimum of 70% (by weight) of non-hazardous construction and demolition waste excluding naturally occurring material defined in category 17 05 04 in the List of Wastes shall be prepared for re-use, recycled or undergo other material recovery" (including backfilling operations using waste to replace other materials) [9]. Urban solid wastes contain 30–40% of waste coming from construction and demolition activities [10]. In Italy, the ratio of construction and demolition waste, which is prepared for re-use, recycled or utilized material recovery was 98% in 2018 compared to 88% of the whole European union. Mineral wastes from construction and demolition are usually concrete, bricks, and gypsum waste; insulation materials; mixed construction wastes containing glass, plastics and wood; and waste bituminous road-surfacing material [11]. According to Eurostat in 2018 Italy generated almost 41 million tons of non-hazardous waste from construction and demolition activities (Table 1), 21% more than in 2012.

Table 1. Total major wastes generated in Italy in 2012 and 2018 [7].

Waste Category	Quantity Generated in 2012 (tons)	Quantity Generated in 2018 (tons)
6.1 Ferrous metal waste and scrap	9,234,009	9,917,644
6.2 Non-ferrous metal waste and scrap	1,021,982	1,276,126
6.3 Mixed metal wastes	511,422	637,120
7.1 Glass wastes	2,462,787	3,089,553
7.4 Plastic wastes	2,781,865	4,393,791
7.5 Wood wastes	3,847,633	5,253,267
12.1 Construction and demolition wastes	33,916,487	41,265,770
Total CDW–non-hazardous	**33,756,796**	**41,023,023**
Total CDW–hazardous	**159,691**	**242,747**

According to Eurostat figures, at the national level 96% of CDW were recycled in 2018 (90% in 2012), and the amount of CDW which went to landfill was reduced to 1.7% from 2.4% in 2012. The recycling rate has been steadily growing (Table 2) [12].

In recent years, Circular economy concept attracted an increasing attention. Its goal is to offer an alternative method of traditional dominant model of consuming natural resources. It focuses on three main approaches: reduction, re-use and recycle [10,13]. Many world countries are trying to decrease their construction and demolition waste by implementing various legislations and improving awareness through different measures to reduce the effects on the environment. Information is available on C&D waste production in each part of world in relation to the recycling activities and existing policies and legislation on disposal of C&D waste [8]. Whilst coarse recycled aggregates generated from construction and demolition waste are permitted by many specifications for various applications in road construction, a necessity exists for developing a high- value market for the recycled aggregate fines. Potential exist for a higher market price for recycled aggregate (RA) fines due to their residual binding properties. In fact, some RA fines possess hardening properties, such as recycled concrete aggregate, whilst others have pozzolanic properties, such as bricks and ceramic wastes. In both cases the binding capacity of these materials will significantly contribute to the cost benefits, for example by reducing the binder requirement in hydraulically bound mixtures (Figure 2) [14].

Table 2. Treatment of construction and demolition mineral waste in Italy in years 2012 and 2018 [12].

Performed Action	Quantity in 2012 [tons]	Quantity in 2018 [tons]
Deposit onto or into land	919,503	732,347
Land treatment and release into water bodies	375	0
Incineration/disposal (D10)	2720	2188
Recovery other than energy recovery -Backfilling	160,290	147,623
Incineration/energy recovery (R1)	0	585
Recovery other than energy recovery -Except backfilling	29,782,235	39,481,612
Total waste treatment	**30,865,123**	**40,364,355**

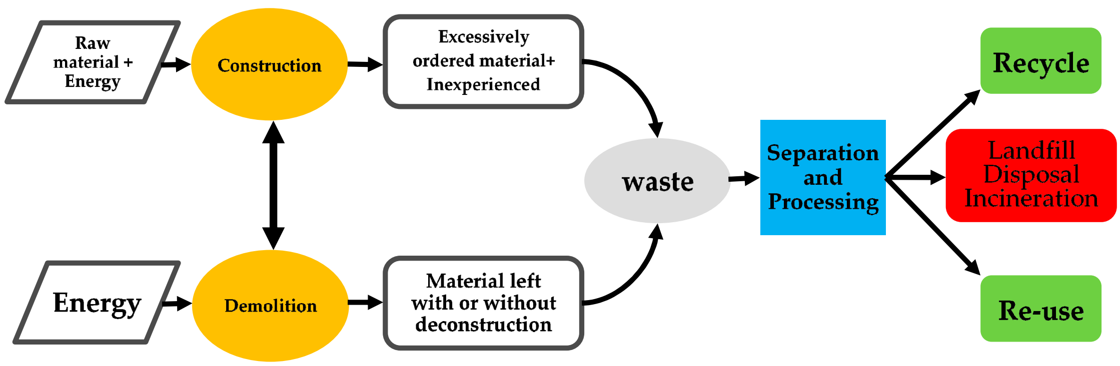

Figure 2. Circulation of construction materials from raw state to end-use and disposal [8].

2. Main Types of CDWs

There are three main categories of CDW aggregates: Recycled concrete aggregates (RCA), Recycled masonry aggregates (RMA, sometimes Crushed Clay Masonry-RCM) and Mixed recycled aggregates (MRA–also mixed demolition debris) [15,16]. However, most construction and demolition blends are combined of these types and the portion of each material can affect the properties of the total blend [17–21]. Additionally, other materials like ceramics can exist in some blends [17]. Moreover, another type of aggregate waste, reclaimed asphalt pavement (RAP) aggregate produced from crushing mixes bounded with bituminous binder, is also a typical substitute material for using in pavement and geotechnical usages [15,22]. The composition of CDW aggregates highly depends on their source and the processing method. The diversity of the construction operations and methods naturally mean that RA sourced from construction and demolition activities will change in quality and composition, which will definitely produce new construction materials of varying quality. Furthermore, the method of demolishing a building structure may be effective, and it could be either conventional or selective. The selective demolition approach, along with more control on the quality of the CDW materials obtained, ensures a substantial reduction of the environmental effects specifically caused by climatic change, acidification, summer smog, nitrification and release of heavy metals. These result from the emission of a wide array of compounds and elements, all of which are identified to be major pollutants [23].

Construction and demolition activities result in a wide range of materials including concrete, wood, glass, metals, as well as some harmful component. Complexity and composition of these materials make the separation of C&D wastes a difficult mission. Some materials such as wood, glass and metals can be recycled directly or in few circumstances can be reused without additional processing, while, concrete waste has different features which make it unique. It is unavoidable to recycle most of waste concrete due to the large amount of natural resources being exploited for its production. This will provide a route to significant decline of the waste being directed to landfills and in parallel possibility of conserving natural resources. A major part of waste concrete is recovered in the form of RA containing attached mortar on its surfaces which brings in some of the limiting aspects of the recycling such as: increased water absorption, lesser strength and high penetration capacity of chloride [8].

Independently from the source, the overall combination of the recycled coarse aggregates are usually analyzed in accordance with the EN 933-11 standard. Different components can be often distinguished in CDW mixes (Figure 3), such as Asphalt (R_a), Ceramics (R_b), Cement- based materials (R_c), Light particles (L), Unbound aggregates (R_u), Glass (R_g), Others: wood, plastic, metal (X_o), Gypsum (X_g) [24].

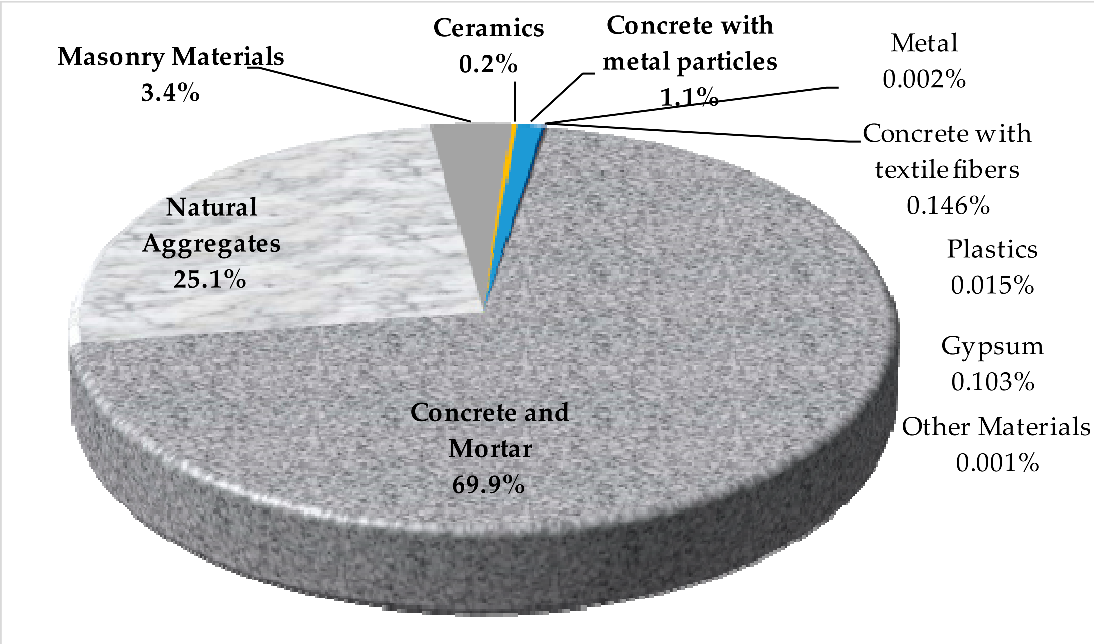

Figure 3. Example of components of recycled aggregates (% of the total dry weight) [25].

As mentioned above, recycled concrete aggregates mostly differ from natural aggregates in that they are consisted two different parts: the natural aggregates and the attached cementitious mortar. As described, the mortar is the origin of some weak properties of the recycled aggregates: lower density higher moisture absorption, higher abrasion and sulphate content [26,27]. These features might have a negative effect on the recycled concrete quality, mainly influencing the material's performance linked with strain (elasticity, shrinkage, and creep, durability) and to a less degree, strength. Implemented test on aggregates for measuring the amount of adhered mortar content can be the source of discrepancy in the result: in between 25% and 70% using the treatment of samples with hydrochloric acid solution, from 25 to 65% for the making a different colored concrete, and 40–55% with thermal treatment. Furthermore, the amount of mortar attached to the fine fraction is more than for the coarse fraction. Thus, the specific gravity decreases as the percentage of coarse RA increases [27]. Finally, skid resistance might also decrease in RCA mixes because of the weak adhered paste on the surface of aggregates [4].

3. Preliminary Characterization of CDWs

Two main categories exist for preliminary assessments of aggregates implemented for construction of various layers of pavements: the geometrical characterization (e.g., size distribution, shape index, flakiness index, etc.) and the physical characterization (specific gravity, water content and freeze-thaw, etc.). Most of these characteristics can be used for the classification of the recycled aggregates which can contribute to the CE marking of the materials if European Standards are used for the tests. As for the chemical characterization of these materials, most of the local regulations require specific tests on the waste product in order to assess their potential effects on the environment. Despite this being a fundamental aspect of the recycling process, it will not be considered in this review.

3.1. Size Distribution

The particle size distribution (PSD) has a determining role on the mechanical properties of the recycled materials and consequently, has a major influence on the pavement structural behavior. The distribution of particles of CDW products may be different based on the source type and composition, on the procedure of demolition and on the planned application of the material. PSD is generally specified in terms of upper and lower grading limits and there are several classifications of aggregates mixes in standards based on their size range. Recycled concrete aggregates mainly have components of both gravel and sand, with a portion of fines (smaller than 75 μm based on ASTM D2487, 2006) usually lower than 10%. Around 75% of CDWs were crushed into the gravel fraction and the remaining in the sand fraction. Majority of the RAP batches were considered gravel as per BS 5930, relying on the considered standard [15] (Figure 4). There are several local and global standards and also technical recommendations of different institutions, which fixes the limits for the gradation of materials used in unbound layers of pavements. Moreover, there are some indexes like uniformity coefficient (C_u) which give rough information about the distribution curve.

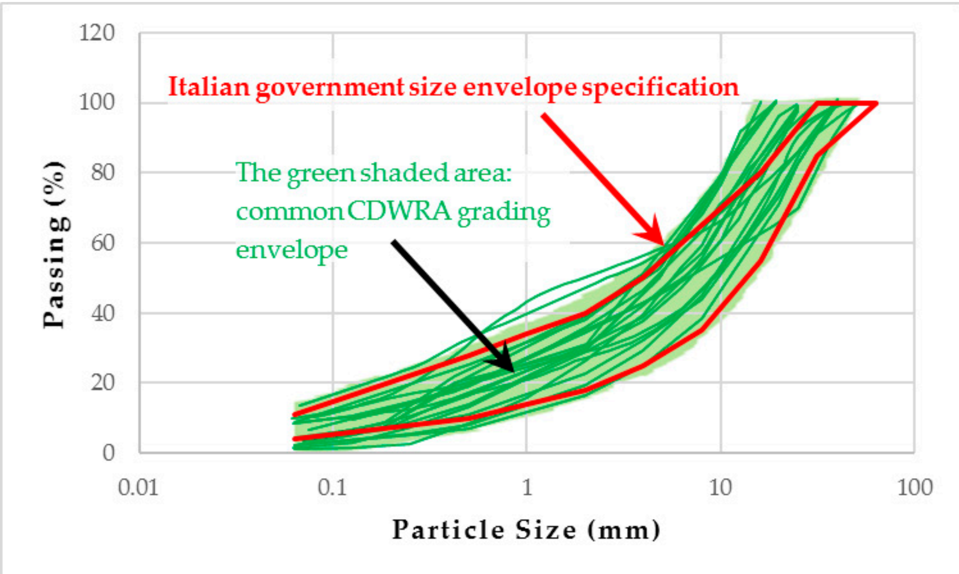

Figure 4. Particle size distribution curves of CDW recycled aggregates from previous researches [24,28–35].

3.2. Flakiness and Shape Indexes

Flakiness index is an indirect measure of the tendency of particles to break during compaction and under the traffic load of the service period. Some mechanical properties such as stability against permanent deformation and load -bearing capacity are linked to the resistance of particles against breaking and flaking. One of the reasons for studying the flakiness of particles can be based on the experience that, with a high proportion of such particles, handling difficulties can arise, accompanied by segregation of larger particles. Some authors tried to define the limits on particle size distribution change due to breakage with respect to the mid-size dimension. Generally, in most of the researches it is shown that CDW aggregates satisfy the flakiness limits [36]. Care should be taken for mixtures with high percentages of ceramic and masonry which usually have flat and elongated particles. These are also the lighter components of RA mixes. Therefore, it is not uncommon that a mixture characterized by flakiness index within the specifications limit (by weight) has a volume of flat and elongated particles higher than 50% of the total volume mixture.

The shape of a crushed particle depends on the type and condition of the equipment used to carry out the crushing and on the nature of the original rock, as well as on other variables related to the age of the material and its exposure to climate. In general, a high shear strength mixture is achieved with highly angular stones. There are different methods for specifying particles shape, using words such as "cubic" or "angular" or some methods based on the percentage of crushed faces of particles. It is known that an angular material will tend to have a high angle of internal friction (and therefore a high stress ratio at failure). Angularity is not a property which is readily quantified. Most methodologies rely on description and visual categorization as counting of apexes or faces is possible, but this takes no real account of the sharpness of the edges between faces and therefore cannot be relied upon to give a consistent measure [37]. Shape index is rarely studied in CDW recycling. As an example, Cerni and Colagrande have found a value of 28% as shape index for CDW aggregates [31]. Cardoso et al. declared that, independent of the volume decreasing of previous mortar, two or more crushing stages typically lead to rounder and less sharp particles; if RCA only applied an initial crushing process, they will usually show higher shape and flakiness indexes than natural aggregates [16].

Some studies have worked on the changing of particle shapes during Los Angeles abrasion test and Proctor test. Leite et al. showed that despite the fact that cubic grains represented the majority in the cementitious materials, flat and elongated CDW aggregates change to cubic particles after both intermediate and modified Proctor impulse compaction. It is also stated that most of the breakages occur on the coarse fraction at the initial stages of compaction, when the material is not yet densified and the mobility of the particles is facilitated [34]. Moreover, It was shown that presence of ceramic would increase the flakiness and the flakiness index of the batches consisting totally from ceramic rubble could reach up to 40, which is more than most of the limit values [24]. The results of flakiness index for construction and demolition waste considered in different publications are shown in Table 3.

Table 3. Flakiness index values for CDW aggregates.

Researcher	Reference	Flakiness Index (%)
Barbudo et al.	[17]	15
Silvia et al.	[21]	8–30
Vegas et al.	[24]	9–40
Cerni and Colagrande	[31]	26.5
Jiminez et al.	[38]	8–19
Morafa et al.	[39]	12–20
Nataatmadja and Tan	[40]	6–14
Gómez-Meijide and Pérez	[33]	4.5
Del Rey et al.	[35]	12.8–24
Herrador	[30]	12

3.3. Specific Gravity

The specific gravity of natural materials commonly used in geotechnical and paving applications can vary depending on the material type and it ranges between 2.60 and 2.75 or more on average. As well as in various calculations of soil mechanics, physical specifications like porosity, void ratio and weight- volume ratio, are determined by the specific gravity of materials. The average specific gravity of RCAs is relatively higher than that of the other types of recycled aggregates. Lower specific gravity of RA is essentially due to the presence of: (1) adhered cement mortar and its porous nature; (2) bitumen coating (in RAP) which has a density value normally lower than 1.10 kg/m^3; or (3) containing masonry and lightweight materials (in CDW) [15]. The results and values of specific gravities for construction and demolition waste considered in different publications are shown in Table 4.

Table 4. Specific gravity values for CDW aggregates.

Researcher	Reference	Specific Gravity (gr/cm^3)
Barbudo et al.	[17]	2.240
Herrador et al.	[30]	2.040
T. Park	[41]	2.533
Poon and Chan	[42]	2.380
Gabr and Cameron	[43]	2.575
Tahmoorian et al.	[44]	2.370
Agrela et al.	[45]	2.340
Tahmoorian et al.	[46]	2.408

4. Geotechnical and Mechanical Characteristics

4.1. Compactability

Some engineering properties of soil or other unbound paving materials, such as shear strength, internal friction and water drainage improve by reducing the volumetric ratio between the voids and the particles due to rearranging and repacking of grains with mechanical compaction. Several types of assessments such as standard Proctor and modified Proctor tests are used to evaluate the compactability of soils. The goal is to determine the optimum moisture content (OMC) at which soils or mixtures of aggregates mixes attain the densest condition, demonstrating their Proctor Maximum Dry Density (MDD). Differences between these test procedures include the weight of the hammer used (2.7 kg for standard proctor and 4.9 kg for modified proctor) and the falling height of the hammer (35 and 45 cm) [15].

The final outcome of the compactability test is the moisture -dry density curve. The moisture -density curves are in fact a presentation of the sensitivity of the density with respect to the change in moisture content for the materials [47]. Typical curves are shown in Figure 5. Materials with flat curves can tolerate a greater amount of variation in the moisture content without compromising much of the achieved density. On the other hand, during compaction, moisture content of materials having sharp curves which are sensitive to the change in moisture should be close to the optimum value [42].

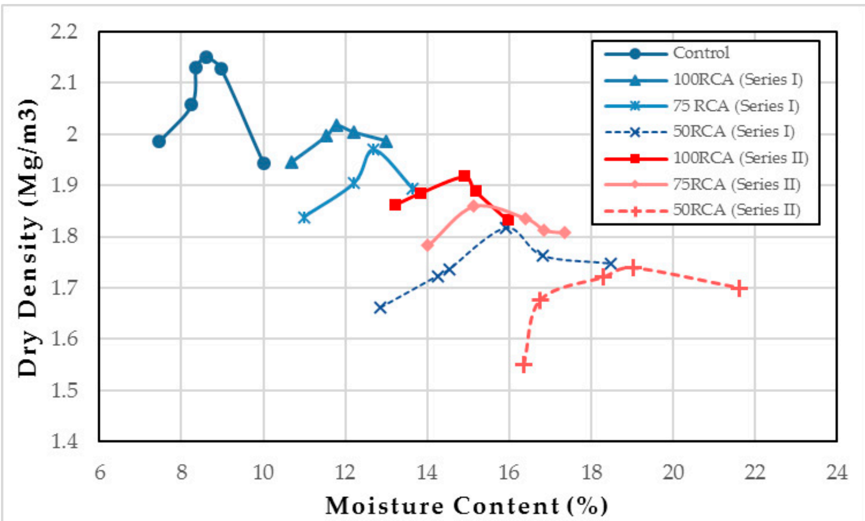

Figure 5. Moisture- dry density for blends with different percentages of crushed clay bricks and recycled concrete aggregates. Serie I has recycled concrete aggregate as fine aggregate and Serie II has crushed clay brick as fine aggregate [42].

Generally, recycled aggregates have comparatively higher water absorption due to the attached adhered cement mortar on RA, or the porous character of the aggregates such as clay bricks. This causes an increase in OMC which is greater than 10% for most of the RAs, those of recycled masonry aggregates and mixed recycled aggregates being relatively higher than that of RCA [15]. A pre-wetting process might be considered for the assessment of compactability of these materials.

Moisture and dry density are directly influenced by type and combination of CDW aggregates. Poon and Chan in 2006 clearly demonstrated that by substituting the recycled concrete aggregates with crushed brick, the optimum moisture increases while the MDD decreases linearly (Figure 5) [42]. Leite et al. evaluated the compaction of CDW aggregates by standard and modified Proctors. The standard effort corresponds approximately to 50% of the modified effort and it is used for sub-bases in some countries like Brazil. Authors reported the values of 13.5% for optimum moisture content and 18.2 kN/m^3 for maximum dry density for the modified proctor test, and 14.6% and 17.6 kN/m^{-3} for standard Proctor test [34]. The values of Proctor test for different studies on CDWs are shown in Table 5.

Table 5. Compactability test results from literature review.

Researcher	Reference	OMC	MDD (kg/m^3)
Barbudo et al.	[17]	11.6%	1950
Arulrajah et al.	[19]	10.7% (Brick dominant)	1982
Vegas et al.	[24]	6.52%	1885
Leite et al.	[34]	13.5% (Modified) 14.6% (Standard)	1820 (Modified) 1760 (Standard)
Jimenez et al.	[38]	12.7%	1910
Morafa et al.	[39]	12.5%	1940
Herrador et. al.	[30]	9.4%	2040
Agrela et. al.	[45]	11.5%–12.4%	1960–1990
Arisha et. al.	[28]	12.7%	1860
Jimenez et. al.	[32]	12.3%	1855
Rahman et. al.	[48]	12.5%	2100
Azam and Cameron	[49]	11.6%–12.5%	1857–1919

4.2. California Bearing Ratio

California Bearing Ratio (CBR) is widely used for characterizing subgrade, subbase and base materials of pavements. It has been associated with pavement service behavior and design methods and it has been at the basis of several airfield pavement design methods. Considered reasonable and sound, it could be assessed using simple test equipment in the laboratory or in the field and at moisture -density conditions existing under the pavements [50]. Some authors pose doubts on the test's relevance and usefulness because of the difficulty in producing a sample in a mold with a 152-mm diameter at the same conditions expected in the field [51]. The CBR test is usually done in two different modes of un-soaked and soaked (by immersion) in water. Several standards are available for the testing procedure, one European standard (EN 13286-47), two American (AASHTO T193-72 equal to ASTM D1883) and one English (BS 1377).

Vegas et al. reported a range of 76–130% for different batches of CDW aggregates tested in different collection times after 4 days of immersion. These values improved by increasing the time of soaking in the water up to 90 days to the range of 138–185%, which could be because of remaining binding potential of the cement in the crushed concrete (Figure 6) [24]. By evaluating the relation between dry density, moisture content and CBR value, O'Mahony showed that for equivalent dry densities, the CBR index decreases by increasing the moisture content [51]. Barbudo et al. measured the California Bearing Ratio for different types of mixes with different compounds, compacted by modified Proctor in their optimum moisture content, in order to evaluate the influence of different crushing and screening methods, as well as of the mix proportions on the bearing capacity. After 4 days of soaking in water, recycled concrete aggregates showed a CBR index of 55–138%, with an average of 100% while different mixtures of concrete and brick fell in the range of 40–110%, with an average of 74. This means that concrete aggregates can reach higher bearing capacity than mixed batches [17]. Leite et al. reported 73% and 117% for CBR values of standard and modified compaction mixes of CDW aggregates [34]. Arisha et al. reported CBRs of around 160% for mixed aggregates, which dropped to almost half for recycled masonry aggregates. This could be related to the content of residual free lime in CDW mixes and the cementation process [28]. Morafa et al. showed that for oil- contaminated RCA aggregates, there is a limit value of contaminants corresponding to the maximum CBR and density. CBR was measured in a range of 72–85% for four oil-contaminated concrete aggregates [39]. Gabr and Cameron tried to implement an experimental relation between CBR index, and the moisture content of 4-day soaked samples; increasing density and CBR results were reported by increasing moisture content in all recycled materials. Recorded values are in the ranges of 90–143% and 120–215% for two kinds of Australian CDW aggregates [43]. Jiménez showed that recycled concrete aggregates after soaking for 4 days, exhibit CBR values between those of natural aggregates and mixed debris. CBR values in the range of 97–137% are reported by the authors [52]. These results are shown in Table 6 along with some other data.

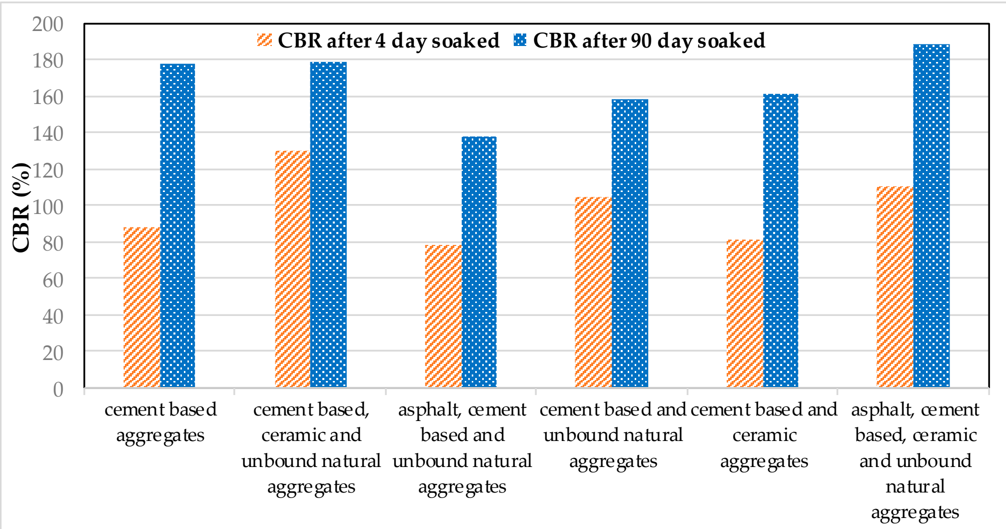

Figure 6. CBR development for different types of Construction and Demolition mixed recycled aggregates after 4 and 90 days of immersion in water, based on the various combination of compounds [24].

Table 6. Literature results of California Bearing Ratio test for different CDW materials.

Researcher	Reference	Standard Proctor		Modified Proctor	
		Soaked	Unsoaked	Soaked	Unsoaked
Jiménez et al.	[17]	-	-	74% (mean)	-
Vegas et al.	[24]	-	-	76–197%	-
Cerni and Colagrande	[31]	-	90%	-	-
Leite et al.	[34]	-	73%	-	117%
Jiménez et al.	[38]	-	-	68%	-
Morafa et al.	[39]	-	-	-	72–85%
Jiménez et al.	[35]	-	-	-	63.7%, 67.3%
Poon and Chan	[42]	35–62%	35–62%	-	-
Gabr and Cameron	[43]	-	-	90–215%	-
Arisha et al.	[28]	-	-	70–153%	-
Jiménez et al.	[32]	-	-	62–94%	-
Lanciere et al.	[53]	35–113%	71–115%	-	-

4.3. Abrasion

Los Angeles Abrasion (LAA) is used to determine the resistance of aggregate to fragmentation or mechanical breakdown because of impact and wearing [15]. Tests in a ball mill known as Los Angeles drum (EN 1097-2) produce a combination of abrasion and crushing, while a micro-Deval test (EN 1097-1) causes only abrasion. In all abrasion tests a certain fraction of the material is exposed to wear and the resulting increase in fines content is measured. For determining the impact strength of the aggregates, the alternative standardized impact test (EN 1097-2) is implemented. The European Los Angeles test is a modification of the original test method used since the 1920s. In the most recent standard five kilos of the 10–14 mm fraction of the material is exposed to 500 rotations in a steel drum together with 11 steel balls.

Aydan et al. showed that weight loss in LAA decreases from 31% to 24% as the substitution ratio of RCA with NA increases from zero to 100% and natural aggregates are stronger in opposing to impact forces in comparison to RCA [54]. Furthermore, in a similar study, Diagne et al. showed that in the CDW aggregates, resistance to abrasion differs by the portion of recycled concrete aggregates (RCA) and recycled clay bricks (RCB). The RCAs have a LAA index of 30% which increases to 36.8 for the mixture composed of 100% of RCB [20]. Barbudo et al. also measured the LAA for natural, concrete recycled and mix recycled aggregates, and showed that mixed recycled aggregates and concrete recycled aggregates have less resistance to abrasion, with average Los Angeles values of 38% and 33%, compared to the natural aggregate LAA coefficient of 21% [17]. Arisha et al. measured the very low value of 83% for LAA of masonry recycled aggregates, which is out of all requirements for utilization of recycled materials. This measure is much better for mix of CDW aggregates, with the LAA result of 47% [28]. Morafa evaluated the aggregates recycled from oil- contaminated concrete waste and showed that the abrasion of RCAs (27%) is much more than virgin natural aggregates (18%), and also the soundness of aggregates could affect the LAA results [39]. Jimenez tried to figure out a relation between particle size and Los Angeles abrasion loss (Figure 7). They tried to prove that the higher is the Los Angeles coefficient, the higher the mean particle size is. A loss of 34% for LAA of recycled concrete aggregates and the range of 31–41% for mixed debris of construction and demolition were measured, which both are higher than the loss for natural aggregates (20%) [32].

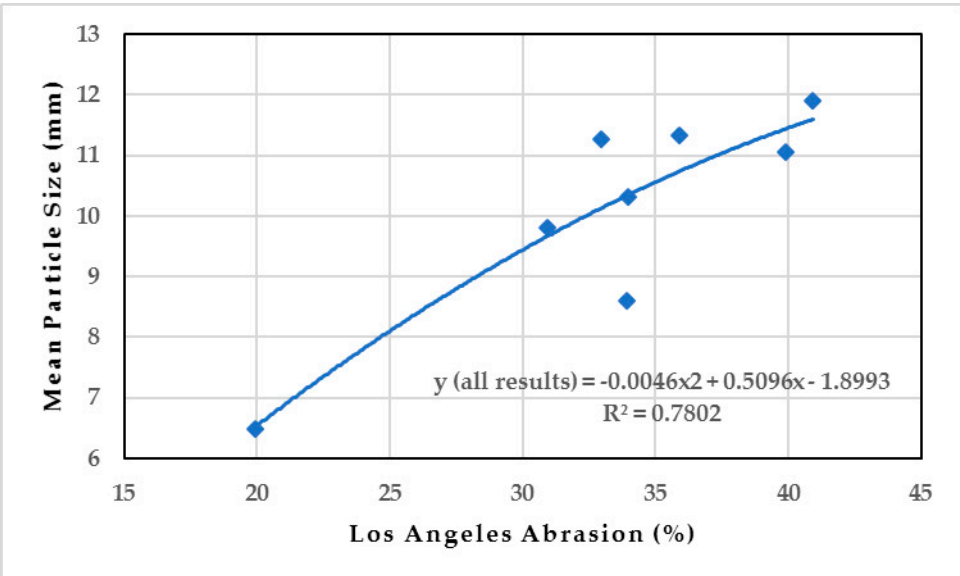

Figure 7. Mean particle size vs. Los Angeles abrasion [32].

De Juan tried to find a relation between the attached mortar and the LAA abrasion rate (Figure 8) assuming that in the Los Angeles abrasion test all the adhered paste of recycled aggregate become powdered, apart from the abrasion induced by the natural aggregate. For this reason, both properties are expected to be correlated. The measured values for Los Angeles loss are in the range of 36–42% for fine aggregates (4/8 mm) [26].

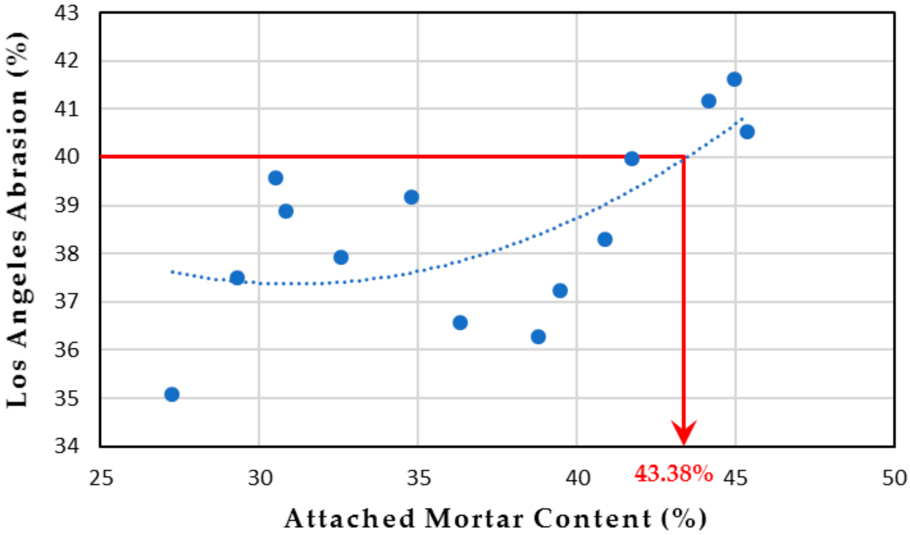

Figure 8. Attached mortar vs. Los Angeles abrasion; 43.38 is the proposed maximum percentage of attached mortar referred to the limit of 40% abrasion [26].

4.4. Resilient Modulus

Pavements are structures which are subjected to large numbers of repeated loads. The resilient modulus of unbound materials represents their stiffness (stress–strain relationship) under repeated loads that resemble traffic loads. It is commonly known that the resilient modulus depicts the attributes of aggregates, such as particle size distribution, density and moisture content, as well as applied factors such as stress and to a lower extent, temperature [15]. Together with CBR test, triaxial compaction test for measuring the resilient modulus is also one of the major material evaluations for various layers of pavements, especially for evaluating the behavior of pavement material under cyclic traffic loads. Although the same compaction energy was utilized in both tests, some facts and disadvantages of CBR may have contributed to the increased observed result could be counted as: First; specimens of CBR test may not be properly representative of the original material as the specimens of resilient modulus. There is a limitation for maximum aggregates size in CBR standard procedure, but the resilient modulus allows the use of the same gradation used in the field. Secondly; the confining stress in the CBR test is not demonstrative of the observed confining stress of the field as the one imposed in the resilient modulus. Thirdly, the measured displacements in the resilient modulus test are in the elastic zone, but this is not observed in the CBR [34].

The main challenge in studying and comparing the resilient modulus is its dependence on the stress condition. The value of the resilient modulus in unbound granular materials is a result of the confining stress level and deviatoric stress. In particular, it is usually possible to obtain the experimental parameter (M_r) related to each pair of tension (σ_3, σ_d) investigated. One of the most used models for resilient modulus of granular materials is the K-θ model ($M_r = K_1 \times \theta^{K2}$), which describes the resilient modulus by an exponential function of sum of principal stresses by a good approximation [55]. Generally, the stiffness stated by the resilient modulus growths as the bulk stress increases. Actually, a rise of θ causes the grains which make the material solid structure to become closer to each other and, consequently, it raises the interlocking degree and the contact areas among them with the consequent reduction of the specimen deformability. Considering an element of soil under the road pavement, the confinement pressure influencing it is the outcome of horizontal compression and contact stress produced by adjacent material and it is a function of the depth. In the altogether, since in recycled materials the stiffness increases remarkably with the confining pressure, it is advisable to use these materials in lower layers. Cerni and Colagrande are convinced that it is reasonable to use a CDW-RA mixture in a lower layer such as the road subbase, where the low vertical loads generated by vehicles do not cause technical necessities and economically convenience for the application of elevated performance, very expensive material. Moreover, the same authors demonstrated that the CDW-RA mixture, even characterized by the presence of minor amounts of binding agents which add cohesive properties to it (such as lime), presented a resilient behavior very close to a common frictional material like a virgin quarry aggregate mixture. The characteristic which proposed such a similarity is low susceptibility to water [31]. Azam and Cameron demonstrated that adding recycled masonry aggregates to recycled concrete aggregates will decrease their resilient modulus and increase the permanent strain of the mixes under triaxial repeated test. Moreover, the moisture content has an important effect on the resilient properties of the mix materials, and a reduction in resilient modulus can occur with an elevation in moisture content. The authors also evaluated the relation between the resilient modulus and matric suction which happens because of the capillary nature of water between aggregates and they identified a simple power model which adequately fits the data between matric suction and the resilient modulus in a single stress stage [49].

Cameron and Azam in their research, mainly investigated the effect of relative moisture content on the resilient modulus of different blends of RCA and recycled masonry aggregates. As shown in Figure 9, an important decrease in resilient modulus happened with an increase in moisture content which becomes steady after reaching 80% of the OMC. The effect of masonry portion on resilient modulus was sensibly clear with a reduction in resilient modulus as the crushed masonry ratio increased [18]. The results of the K-θ model for some completed research on CDW aggregates are shown in Table 7.

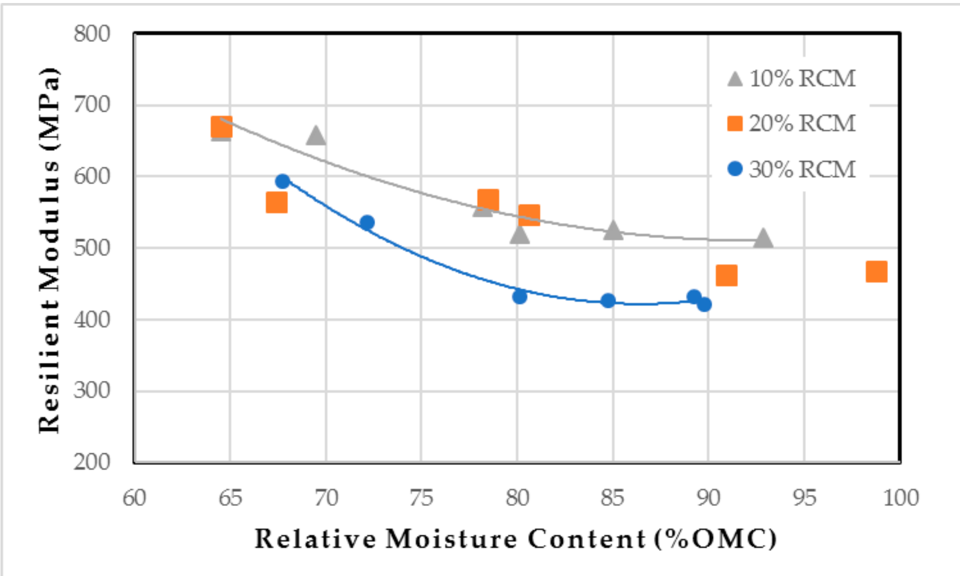

Figure 9. Resilient modulus change by changing relative moisture content in different mixtures of CDWRA [18].

Table 7. Parameters for the modelling the resilient modulus.

Researcher	Reference	Material	K_1 (kPa)	K_2
Arisha et al.	[28]	CDW-RA	15.48	0.54
Cerni and Colagrande	[31]	CDW-RA	3.8–5	0.60–0.64
Leite et al.	[34]	CDW-RA	4.4–5	0.42–0.46
Nataatmadja and Tan	[40]	RCA	14.3–16.7	0.55–0.60

One of the properties which are usually studied together with the resilient behavior, is the development of permanent strain under repeated load and the shakedown (maximum ratio of deviatoric stress to confining stress) limit. This aspect has less importance when studying the low volume or rural road pavements, as the deterioration of low volume roads has less priority compared with other parameters. However, due to the heavy loads that can be applied on rural and farm roads because of the traffic of agriculture equipment and the actual pavement structure thickness, this parameter should be taken into consideration. This should be done in order not to reach the limit of uncontrolled increasing plastic strain of unbound layers in the initial stages of the pavement service, as the rate of plastic deformation could accelerate resulting in fast breakdown of the unbound layer.

Leite et al. studied the shakedown limit in different stress conditions for CDW-RA. The fact that permanent deformation of the CDW layers related to the stress levels must be extremely considered in the case of base layer designing, particularly when a thin asphalt surfacing is exerted, due to the usual high stress levels transferred to the base. Considering the shakedown concept leads to the realizing of the material behavior under traffic loading and to neutralize those pavement damages. It was shown that for a σ_d/σ_3 limit transition from 4 to 6.7, the rate of deformation increases visibly, which should be considered in the design of rural and farm roads for avoiding the degradation of their unbound layers at initial stages of their service [34].

5. Examples of Specific Uses in Unbound Layers of Pavements

The use of construction and demolition waste recycled aggregates (CDW-RA) as a replacement for natural aggregates (NA) in the pavement construction industry is by far the most common application, if compared to their use in the construction of buildings and geotechnical applications. However, within the pavement construction applications, RAs tend to be mainly used in the unbound form and more often in sub-base and base layers and less in hydraulically bound and bituminous bound mixtures [56]. Figure 10 illustrates the most common steps leading from the collection of the CDW materials at the recycling plant, to their management, classification and use in an unbound layer of a pavement.

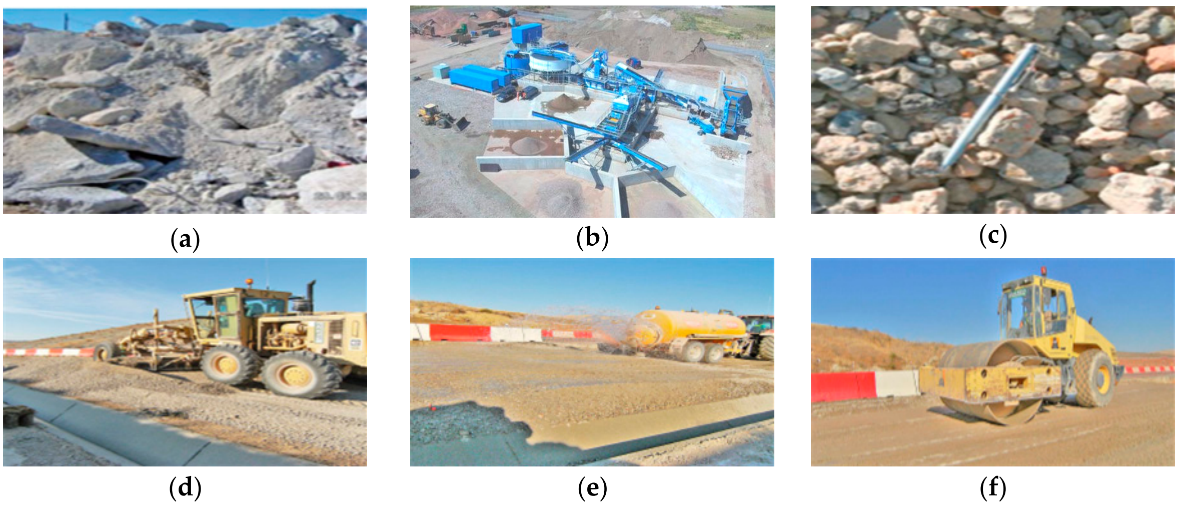

Figure 10. Common steps for the construction of a road pavement with CDW aggregates: (**a**) initial waste material; (**b**) Grinding and classification of various components in a fixed plant (credit: Brewster Bros); (**c**) CDW final product; (**e**) spreading and layering; (**e**) moisture control and (**f**) compaction [30,57].

In 2006, Lancieri et al. studied the performance of roads built by using CDW aggregates by means of the Falling Weight Deflectometer (FWD). Authors tested the unbound low traffic road pavement approximately 4 and 8 years after construction. An improvement in the structural behavior of the layer was observed and was attributed to the self-cementing properties of the adopted CDW materials.

These field experiments were combined with laboratory tests completed in order to study the time change of mechanical features of C&D materials and to assess the effect of compaction methods on the enhancement of resistance recorded with the gyratory compactor. The obtained data and results confirm that road construction could propose a reliable application for C&D waste recycling. It was proved that the E-moduli back-calculated by analyzing the FWD tests, showed a meaningful improvement after 4 and 8 years of traffic, which could be also due to further compaction during traffic. However, the layers built with materials obtained from recycled construction and demolition waste were shown to keep over time a performance that was by no means lower to that of traditional materials. Besides, results both of in-situ and laboratory tests discovered that the load-bearing capacity of the material had substantial sensitivity to the dry density ratio [53].

Herrador et al. constructed a test road section of 80 m in length made with recycled CDW aggregates and designed for a mean daily traffic of 100–199 commercial vehicles per day. The authors also showed that the compaction of the artificial CDW aggregate at the field is more difficult because it needs more water. FWD test showed very satisfying results in terms of load- bearing capacity of CDW layers. Moreover, a simple cost analysis was done by comparing the manufacturing costs of both CDW aggregates and natural aggregates: the cost of the recycled aggregates was higher than the natural ones. The difference in price origins from the fact that the cost of waste cleaning and management is added to the total price of recycled aggregate (2.35 €/t). This is more costly than blasting with explosives (1.47 €/t), which is a necessary budget item in the cost of natural aggregates [30].

Leek et al. studied the performance of three test road sections made of CDW in Western Australia, comparing them with sections made of natural aggregates. This research proved that recycled roadbase aggregates obtained from recycled demolition materials can offer a good quality and high strength base for roads, which can allow increased asphalt fatigue life, because of the reduced deformations. According to the authors, the source of recycled concrete can have a substantial effect on the material rehydration and its possible further excessive stiffness that could cause block cracking. It is suggested that adding masonry, tile and or sand as a fine material into the recycled product may control the excess of stiffness and limit the effects of rehydration, which may not be sufficiently captured by a 28-day unconfined compressive strength test [58].

Jiménez et al. studied the performance of the unbound base layers of two experimental unpaved rural road sections constructed with selected CDW materials. The external factors such as climate and traffic were also considered in the research and the bearing capacity was studied using the plate load test (PLT). It was shown that the change in dry density of layers within the first year is neglectable. It was also seen that vehicle traffic could improve the bearing capacity of CDW unbound layers after some years, which could be attributed to the moisture increase or to the pozzolanic activity in the attached cement mortar of aggregates. The only drawback connected to the use of CDW materials in pavements was identified to be the soluble salt content. All tests of static PLT, FWD and Roughness exhibited excellent engineering properties and these properties were maintained during several years of service under traffic load. As a general conclusion of their research the authors were satisfied with the use of CDW for unpaved rural roads [38].

Del Rey et al. tried to study the use of unbound CDW in subbase and base layers of unpaved rural roads and evaluated the behavior of mixed CDW aggregates with respect to natural aggregates. The density of field layers and moisture content were measured using nuclear density equipment during construction of three test sections. Moreover, static plate load tests were implemented to prepare the load-strain curves and Falling Weight Deflectometer measurements recorded the strain observed at the surface as the result of the dynamic load. Additionally, the degradation of the road pavement was assessed by means of measuring the rut's depth at the surface. It was shown that the average deflection values obtained in the trial sections constructed using CDW aggregates were 63% and 46% higher than those obtained in the section made with natural aggregates. According to the authors, this meant that using CDW aggregates in the subbase would need a stiffer subgrade in order to reach a bearing capacity falling in the acceptable range. A reduction in the elastic modulus was experienced in the section constructed with CDW, which was linked to the low fragmentation resistance of the material. Although CDW underwent higher deformation and had less elastic modulus values than NA, the CDW aggregates used in this study showed an acceptable performance. Overall, the results of the study suggested that CDW aggregates can be utilized in structural layers of low traffic unpaved roads, constructed over subgrades of expansive clays. The authors concluded by recommending the use of CDW in unpaved rural roads with low traffic [35].

6. Conclusions

The number of completed and on-going studies on the possible use of CDWs has increased in the recent years and this gives evidence of the diffuse concern on the sustainability of the construction sectors. In many cases CDW have been proven to perform as well as natural aggregates and in some cases, the residual binding properties have contributed to the development of mechanical properties in time. The use of CDWs in pavements is more likely one of their best applications as their adoption can be calibrated on the basis of their actual laboratory and field assessed characteristics. In most of the cases their constituents are natural aggregates, and this is usually positive for their use as unbound layers.

The experimental methods to characterize the recycled C&D waste materials are the same as those adopted for natural aggregates. Among them, compactability, bearing capacity, abrasion and resilient modulus are usually given priority as their data can be easily considered for technical specifications and in the design processes of pavements.

In rural roads and agricultural paved areas traffic is normally made of slow machinery with large tires and relatively high loads. Surface characteristics such as roughness and skid resistance are in most cases not considered as a design feature and the main concerns are referred to permanent deformations and bearing capacity, especially in the wet seasons and on clayey soils. For the same pavements, the possible change in gradation due to the weaknesses in abrasion of the CDWs can be a minor concern if the two above characteristics are guaranteed. The simplest use of recycled CDWs in rural pavements is as material for a unique top and thick layer placed on the existing soils. According to the research findings in the literature, the main design aspect to focus on should be the actual bearing capacity of the subgrade soils in different moisture conditions. The use of coarser mixes and/or of separation geosynthetics can be a viable solution to maintain the pavement bearing capacity within the limit range.

Once the waste materials have been treated at the recycling plant and the CDW aggregates can return on the market as recycled construction material, their use in pavement layers does not differ from that of natural aggregates. The construction steps are the same and the same machinery can be used for the delivery, laying, grading and compaction of the layers. This is valid for both unbound and bound materials, including the possible application for bituminous layers.

In conclusion, the use of CDWs in the construction of pavements has proven to be a viable solution to exploit their residual positive properties. The recycling processes and the correct classification and selection of the raw waste materials is of great importance in the quality of the final product, i.e. of the constructed layers. Minor additional caution should be used when their use is foreseen in foundation or base layers.

Author Contributions: Conceptualization, C.S. and S.P.; resources, C.S., D.T. and P.T.; writing—original draft preparation, S.P.; writing—review and editing, C.S., S.P. and D.T.; visualization, S.P.; supervision, C.S., All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Conflicts of Interest: The authors declare no conflict of interest.

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A review of studies on laboratory evaluations of agricultural waste materials for rural and low traffic pavements

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Abstract.

To encourage the management of various kinds of waste, which are generated in increasing amounts in modern production and consumption processes, and also searching for ways to reduce the exploitation of virgin materials for construction and development purposes, there is a need of new approaches towards re-using especially solid wastes, including agricultural wastes and bio-wastes. Many completed researches were based on using wastes generated in agricultural and agro-industrial processes and bio-wastes in infrastructure constructions and road pavement layers, especially in developing and agriculture-based countries. This paper presents a thorough and comprehensive review on a number of those wastes to improve the engineering properties of paving materials for applications both in rural and urban constructions, in a circular economy perspective. Here, the categorization of topics is based on the type of application of materials and their adopted condition (burned and unburned, powdered or crushed). Indeed, other categorizations are based on the material itself. Overall, the selected studies clearly show that there is a potential for utilizing various kinds of wastes in road infrastructures by different and innovative methods, and the effort to introduce novel applications of bio-wastes obtained from agriculture industry can open new horizons of infrastructure sustainability and circular economy.

1 Introduction

Utmost of global paved road network is made of asphalt pavements which construction and further fixing rely on constant and regular abundancy of raw sources such as aggregates and asphalt binders. Reliable data on the quarried sand, gravel and crushed stone for production of natural aggregates used for construction are available for only a few developed countries and in recent years. The intensive use of virgin aggregates often makes a challenge about saving of natural non-renewable sources. In addition, operations related to aggregates extraction and processing are also causes of environmental concern. In the light of the above, in the modern-day civil engineering construction, using alternative materials in place of natural aggregate in concretes production (either bituminous or cementitious) can turn them to a more sustainable and environmentally friendly construction material [1]. In parallel, the large amount of solid wastes in many developing countries causes serious ecological and environmental local problems. Discarding these residues is typically by landfilling, burning or recycling. Though , the restricted capacity of landfills, incineration air polluting and reduced substitutes for recycling reduce the safe disposal possibility of those wastes. Hence, their utilization as constituents of pavements can both guarantee their safer disposal and leading the pavement sector to toward more sustainable construction approaches. Priorities exist about the waste hierarchy, which suggest the most effective and desirable actions to be done about the waste: indeed recycling and reusing are among them (Figure 1) [2] .

Usually the effects of material characteristics on the functioning of paving materials (especially asphalt concretes) are evaluated for recycling purposes. Recently emphasis has been given to the studies of effects on structural, durability and ecological effects of paving materials after the utilization of bio-waste materials. Among the solid bio-wastes the crop residues related to primary production (cultivation) and to food processing wastes (from the agro-industrial sector) can be identified as potential materials for the paving industry.

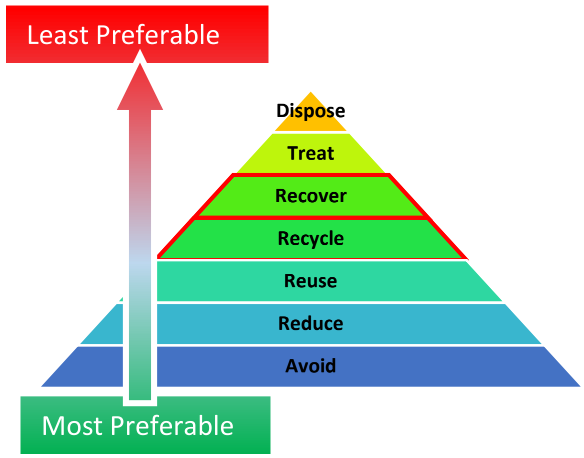

Figure 1. Waste Hierarchy and the highlighted sections which are considered in using Bio-waste in pavement layers [66].

For most Asian and African developing countries, recycling the agriculture bio-waste becomes of unique importance for the abundance of those wastes and for the unavailability (or high costs) of standard construction materials. In these countries, the agricultural industry is one of the main wastes generating activities and produces huge amounts of biomasses. For instance, only India produces residues around 840 million tons per year. Other than the wastes that are created during the harvesting activities, the further operations on agricultural products (grinding, oil extraction, etc.) also creates considerable residues that become waste when they stay unused. It is also well known that many bio-mass by-products with high fuel content, like sugarcane bagasse, rice-husk or waste wood, can be reprocessed as fuel for electric plants. Nevertheless, researches have proposed that residues created after uncontrolled and controlled combustion of farming by-product biomasses could be also effectively consumed as fillers in construction concretes [2]. In other unburned forms, there are additional and various applications in paving materials for those bio-wastes, like coconut crushed shell aggregates and similar powders.

Accumulation of unprocessed agro-waste particularly from the developing countries has an increased environmental concern. Recycling of these wastes into sustainable and green construction materials is a feasible solution for the challenge of pollution and natural resource conservation for future generation. As an example, it is reported that in year 2013 about 600 million tons of wastes from agricultural sources have been generated in India alone [3]. Agro-Industrial waste has become a top research subject all around the world in last 15 years in the light of its potential of industrial use, which reduces the adverse effects of uncontrolled incineration or stockpiling. The available researches and literature give to hand a wide spectrum of inert agro-industrial wastes that is directly applicable in the cement industry as supplementary cementitious materials, given their (post-heating) rich reactive silica content [4–8].

This paper focuses on the possibility of utilizing agriculture and bio-wastes obtained from various sources and aims to provide a broad overview of the existing studies and applications that can lead to potential successful and sustainable paving solutions in developed and developing countries all over the world. The wide number of researches and trials demonstrate the need for new solutions that will always require specific studies prior being implemented to a large scale. The reported literature are here classified on the basis of the final use of the recycled waste. In particular, the uses of bio-waste recycled materials as aggregates, soil stabilizers and binder additives are considered for the purposes of this paper and to stimulate the research of similar solutions.

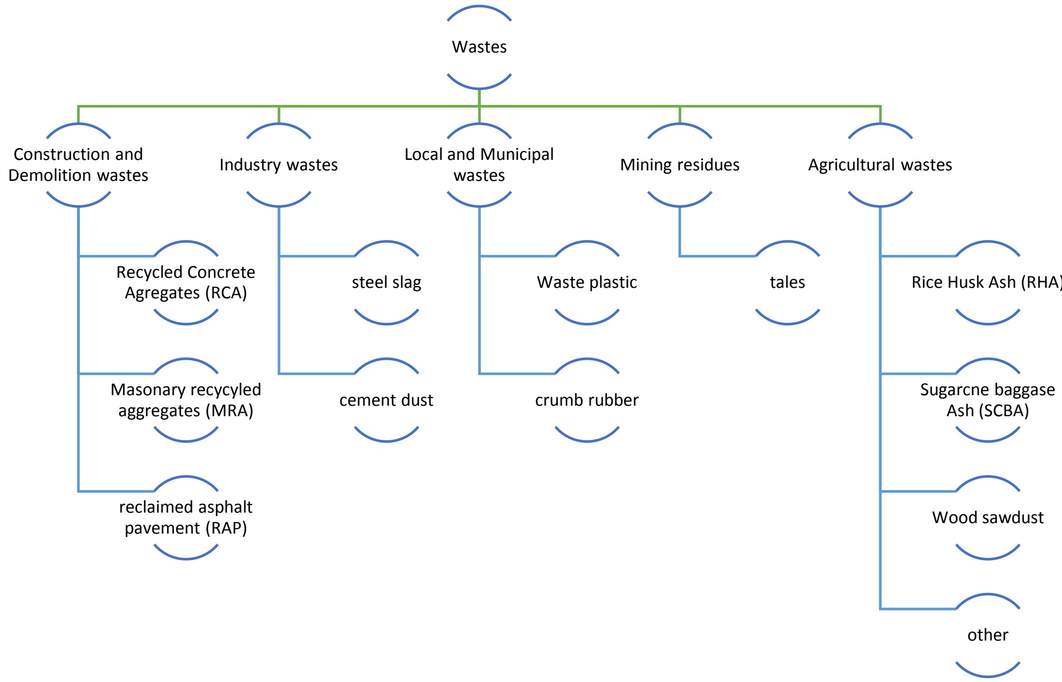

Figure 2. Various categories of generated waste all around the world, including agricultural wastes [9].

2 Recycling bio-waste as aggregates

Aggregates are the most used material for pavements, as a matter of volume and weight portion. The necessity for cost managing of waste disposal and the increasing price of aggregates has directed to an intense worldwide research towards economic application of solid wastes for paving industry. Using agriculture solid wastes as aggregates, could be one of the answers to the present environmental and economic challenges of the paving industry. The following paragraphs provide two examples of materials that have been tested as aggregates in pavements.

2.1 Crushed coconut shells

Coconut crushed shell (CCS) has been investigated by a number of studies in concrete as fractional substitution for coarse aggregates. Outcomes of these studies could be taken as reference for the evaluation of the possibility of exploiting the crushed coconut aggregates also for pavement construction. Coconut shell as a hard and low degradable material if crushed to size of sand can be a potential material to substitute mineral sand. The concrete with ground coconut shell is durable considering its resistance in water, salty, acidic and alkaline environments. The densities of coconut shell solid particles are about 600 kg/m^3 and they can be categorized as lightweight aggregates. It was proven that coconut shell exhibits more resistance against crushing, impact and abrasion if compared to crushed granite aggregates. They can be grouped under the lightweight aggregates category and also except for possible water absorption, there is no necessity to process coconut shell before utilization as an aggregate [1].

Salih et al. measured the CBR values of lateritic soil with the addition of CCS at various depths and showed that improvements in CBR results with the addition of CCS are dependent on density, sizes and distribution of the particles. Moreover, It is observed that the strengthening of soil depends on the interaction of the coconut shell with the soil itself; the research showed also that the optimum aggregate size for crushed coconut was around 1 cm based on its strength, which returned the maximum improvement in terms of CBR values [10]. In a similar research by Ranjitha et al., the inclusion of CCS was found to be an effective and sustainable technique of subgrade stabilizing for weak soils. In this case, the bearing capacity of black cotton soil was enhanced by CSS inclusion. The black cotton soil is a weak soil, generally not suitable for pavement layers construction; it could be effectively strengthened by the addition of CCS as an aggregate and the CBR values of both un-soaked and soaked materials can be improved and can eventually fall in an acceptable range [11].

Table 1. Average values of physical and mechanical characteristics[1] for crushed coconut shells [11].

Material Characteristics	Values
Specific Density	1400 kg/m^3
Bulk density	55 kg/m^3
Water content	4.2%
Humidity absorption	24%
Crushing index	2.6%
Impact value	8.15%
Average Shell thickness	2-8 mm
Abrasion value	1.6%

2.2 Palm Kernel Shells

Palm kernel shells are obtained from the oil palm plant (*elaeis guineensis*), a valuable and economic tree that can be found in Western Africa and is abundant all over the tropics. Palm kernel shells are used mostly for burning for house cooking in most areas where they are available. Moreover, these shells are usually stocked as residue products of the palm oil production. They are not so much utilized in pavements, because of not being abundant in very huge volumes as sand or gravel, or because their utilization has not been promoted . The number of researches done on this by-product for pavement applications are very limited. In one of the rare studies, Ndoke tried to replace natural coarse aggregates in asphalt by palm kernel shell and he demonstrated that palm kernel shells can be used to substitute coarse aggregate up to 30% before severe performance reductions being evident. He also recommended that for high traffic roads, a maximum fraction of 10% palm kernel shells can be used for the substitution, while even complete replacement is feasible for low traffic roads in the rural network [12].

3 Recycling bio-waste as soil stabilizers

In pavement design, the subgrade is often a natural soil that works as a base for the load bearing, which carries the stresses from the above layers. Subgrade is very essential when considering its long-term bearing capacity properties with reference to the overall pavement thickness and costs. The reason is all pavement layers need their principal support from the beneath subgrade. Less stiff subgrades can influence the pavement final design and its structural performance and must be avoided. Thus, there are various stabilizing methods that can be used to reinforce weak subgrade soils, especially when the soil substitution is not practicable. In general, stabilized soil is an optimized composite material obtained from

[1] No standards were mentioned in the reference

mixing soil with stabilizing materials [13]. Commonly used reactive stabilizers like lime or cement can enhance soil strength due to chemical reactions with the soil constituents. Instead of using chemical stabilization, which has been criticized for its possible environmental impacts, there are alternative eco-friendly methods that have been proven to be successful. Indeed, agricultural residues can be recycled as stabilizer to treat subgrade soils in various forms that are mainly represented by geotechnical reinforcement with bio-mats and physical/chemical strengthening with reactive bio-ashes.

3.1 Subgrade reinforcement with bio-textiles

The use of mats/grids for reinforcement to improve weak subgrade soils or embankments is currently a widely adopted method. The tensile strength of the artificial textile and the soil-textile interaction are the main factors that influence the improvement of soil. There are numerous studies available on the effect of bio-textiles on the mechanical properties of various types of soil [10,14–19]. In almost all of them, it is shown that the strength parameters of soils are improved comparing to the plain material. This achievement is significant, especially where there are soft soils (in particular clayey sediments) in areas that produce large amounts of agricultural waste, which can be recycled into bio-textiles or bio-mats. One of the most considered bio-textiles for soil reinforcement is brown colored coir fiber that is obtained from fully ripped coconut. Coir has one of the greatest tensile strength among natural fibers and it is also very durable. Comparatively, coir textiles are very strong and very resistant to abrasion. They should be protected from ultra violet radiation of sunlight during processing in order to provide their best performance in time. Woven coir geotextiles are presented in diverse mesh sizes ranging from 3 to 25mm. Some typical properties of coir fibers are presented in Table 2.

Table 2. Properties of coir geotextile [14].

PROPERTIES	VALUES
Mass/unit area	0.7 (kg/m^2)
Thickness at 20 kpa	6.8 (mm)
Puncture resistance	26 (mm)
Tensile strength	Dry: 8.76 (kN/m), Wet: 7.66 (kN/m)
Shear strength	3.2 (ton/m^2)
Permeability	12 (min^{-1})
Price	0.25 $/kg

The use of various types of coir textiles as reinforcement of weak subgrades is studied by P. Vinod and Minu Michael (2009). The soaked CBR tests were done on reinforced and unreinforced soil. The role of depth position and stiffness of the bio-textile on the properties of reinforced sections were investigated by using five different types of textiles. The outcomes revealed that the implementation of coir textiles increased the bearing capacity. The maximum CBR increase for different varieties of coir tested bio-textiles was found to be in the range of 37% to 97%, [20]. In a similar work, Anusudha et. al. carried out an investigation over the reinforcement behavior of the coir geotextile placed at the interface of granular subgrade and sub-base layers and demonstrated that using coir bio-mats as a reinforcing material for pavement over weak subgrades lead to a considerable improvement in bearing capacity and stress distribution. Also, the type of woven coir affects the strength results, as an example, H2M5 (grade II) coir improve the CBR up to 21%, comparing to 9% improvement by H2M6 (grade I) which are shown in Figure 3.

Figure 3. Two samples of coir geotextiles. Left: H2M5 and Right: H2M6 [21].

3.2 Stabilizing with bio-ashes

Agriculture products are all organic materials consisted mostly from carbohydrates, which contain energy driven from sun by the plants, and they can burn. Most of agriculture wastes in developing countries are used to generate heat and energy by incineration and the residue would be ash, which could be recycled. There are many kinds of applications for these ashes, especially in civil engineering where these materials could be used together or substitute sands, gravels and other aggregates usually obtained from natural sources. Pavements, in particular those built for rural roads or low traffic loads, are a potential application for recycled ashes and can contribute with a positive effect on the environment by avoiding their disposal and allow their use in subgrade soil stabilization, in layers mixes and as binders' additives. In the following sections the use as stabilizers is described with examples taken from the literature.

3.2.1 Palm Oil Fuel Ash (POFA)

Palm Oil Fuel Ash is generated from the burning of palm husk, fiber and oil palm shell in the unrefined palm oil production procedure. Only a limited number of researches investigated the application of POFA in pavement materials because of the limited volume of POFA production in the world [22]. Majorly produced in south Asia in an order of over 10^8 kg per year, it displays high pozzolanic characteristics because of the comparatively prominent silica percent (55 to 65). Because of its pozzolanic properties, asphalt mixes modified with POFA recorded comparable stability and higher rutting deformation resistances, moisture susceptibility and cracking under fatigue comparing to traditional mixes using fillers of limestone [2]. In another study by Mahmood et al., POFA was added to peat, which is a soft organic soil abundantly found in Malaysia and South-East Asia, in order to study the improvement of its mechanical properties. It was shown that POFA increases the dry density of peat soil in a scale of 4 folds comparing to unprocessed peat value. Also, the increment in POFA addition results in a relating rise in the CBR number from 31 to 42 times, comparing with unprocessed peat [22].

3.2.2 Palm Kernel Shell Ash (PKSA)

Being a by-product of POFA, Palm Kernel Shell Ash (PKSA) is obtained from the controlled burning of palm kernel shells at a temperature range between 600 to 1000°C. Numerous experiments on the oxide composition of palm shell and palm kernel shell ashes proved that both have greater alumina and silica substance, which puts them among reliable pozzolan materials.

In a study done by Onyelowe et al., it is shown that the humidity, plasticity index and liquid limit of pozzolan stabilized lateritic soil decreased by the inclusion of coconut shell husk ash (CSHA) together with PKSA. These properties decrease drastically by kernel shell husk ash more than that of coconut shell husk ash. The plastic limit enlarged by adding different percentages of CSHA and PKSA, but CSHA addition increased the plastic limit more than adding PKSHA, therefore indicating that CSHA is more abrasive plastic than PKSA, which diminishes more the moisture content than CSHA. Similarly they showed that

Unconfined Compressive Strength and California Bearing Ratio values both in soaked and un-soaked conditions, improved by addition of PKSA [23].

3.2.3 Rice Husk Ash (RHA)

Natural jackets of rice grains which form during their growth is called Rice husk and it is a very abundant solid waste in Asian countries. RHA is a by-product obtained from burning rice husks as an energy supply at temperatures in the 600- 800 °C range (Figure 4). This method generates amorphous silica ash, a powder with huge surface area of ultra-fine non-spherical and non-agglomerated particles. Also, RHA is produced by not-controlled open combustion in many zones, which is comparatively more economic, although generating ecological pollution. In various relevant researches, fractional or full substitution of RHA have contributed to the production of superior performing mixes than those with conventional fillers.

Figure 4. Rice husks (left) and Rice Husks Ash (RHA) (right) [24].

In 2007, around 108 tons of rice husk were produced all around the world [25]. Abundant value of siliceous content in rice husk ashes (Table 3) shows it has considerable possible pozzolanic features. The characteristics of RHA relies on climatic and local conditions and the fact that husk is subjected to a full destructive burning or only partially ignition. Based on range of temperature and ignition time, various crystalline types or amorphous forms of silica are produced from RHA in terms of zero-carbon , low carbon ash or high carbon char [26].

Recent researches [8,9,33,24,26–32] exhibited that the important application of RHA is in strengthening and increasing soil capacity for infrastructure foundations. In countries with major rice production, the application of RHA for soil strengthening is possible be admitted considering decrease in waste dumping cost and saving non-renewable resources. The researchers performed various approaches and volumetric proportions with several hydraulic activators and recycled by-products, assessing their effects on different soil types. However, some researchers [13,28] conclude that due to the low cementitious characteristics, RHA should be blended with the usual stabilizing agents like cement and lime aiming an operative and effectual soil stabilization. Behak investigated the compatibility of RHA and lime on diverse sand soils. He used x-ray diffraction and ignition loss analyses on ash, followed by unconfined compressive strength test (UCS) on the compacted experimental mix containing RHA, lime and sandy soil. In this research, RHA added from 0- 20% with maximum 10% lime. Outcomes showed an increase of UCS by passing time as seen for all studied mixes of lime and RHA [28].

Table 3. Chemical composition of RHA from different researches.

Oxides	[35]	[24]	[8]	[36]	[5]	[29]	[34]	[24]	[8]
CaO	1.58	1.25	8.95	1.57	1.21	4.9	0.51	1.25	8.95
SiO_2	88.23	90.89	77.27	90.80	82.14	67.3	93.2	90.89	77.27
Al_2O_3	10.8	0.93	3.59	3.5	1.34	1.36	0.59	0.93	3.59
MgO	0.58	0.81	5.85	1.20	1.96	1.81	0.41	0.81	5.85
Fe_2O_3	-	0.47	9.85	1.32	1.27	0.95	0.22	0.47	9.85
K_2O	4.23	2.34	4.08	0.24	2.09	-	2.93	2.34	4.08
TiO_2	0.07	-	-	-	-	-	-	-	-

In a research by Basha et al., the influence of cement and RHA stabilized soils on the liquid limit (LL) and plasticity index (PI) of the various residual soils were investigated. It was shown a reduction in plasticity of RHA stabilized-residual soils as an outcome of increase in LLs and plastics limits. The fact that OMC increases by addition of RHA made the researchers believe that the reason is increasing water absorption by RHA due to its porous nature, which was followed by decrease in MDD. Reducing dry density specifies that it requires less compaction energy (CE) for achieving its highest dry density, which is a positive outcome. It is demonstrated that the combination of cement and RHA has a more effective influence on UCS and CBR than RHA solely, and authors concluded that RHA alone is not a suitable stabilizing agent [13]. In a similar study by the same author, it is shown that an analogous influence happens on soils rich in kaolinite and bentonite; despite the differences in UCS when adding RHA are less than when cement is added. They concluded that a optimum mixture with 6-8 % of cement and 10-15 % RHA improves the properties of soils [37]. Similar optimum percentages were also observed in a research on laterite soil by Alhassan and Mustapha, who showed that with each specified cement content, CBR values increase by increasing RHA amount, despite decreasing in MDD [25]. In soft clayey soils of with high plasticity (CH), as reported by Chakraborty et al., the value of un-soaked and soaked CBR in samples compacted at the optimum moisture content is about 2.40% and 2.15%; hence these soils required stabilization before the construction of any type of pavement. The authors, tried to strengthen these soils adding lime and RHA, and demonstrated that the stabilized material can be used as a sub-grade constituent when stabilized with 6% lime and 6% RHA; in fact, the value of un-soaked and soaked CBR improved appreciably if compared with the original soft clayey soil [34]. Increasing CBR and UCS despite decreasing MDD by addition of RHA, is also proven in the two research works done by Nasiri et al. and Jayashree and Yamini Roja [31,33].

Muntohar also tried to optimize the additive amount of RHA and lime on expansive soil, which is a mixture of kaolinite and bentonite, and he drew a mixtures design chart based on the reduction of plasticity index and increasing of unconfined compressive strength (Figure 5) [38].

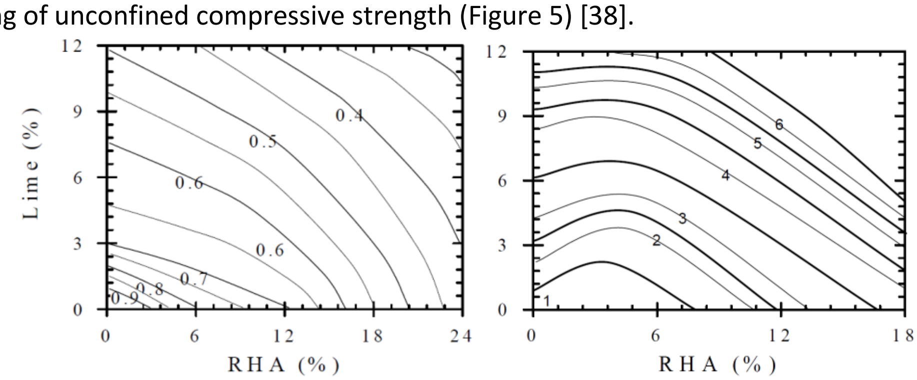

Figure 5. Diagrams for mix design in terms of decreasing Plasticity Index (left), increasing of Unconfined Compressive Strength (right) (Curve numbers are plasticity index and increase ratio of UCS of stabilized to un-stabilized soils)[38].

In two other researches Alabi et al. and Behak concluded that UCS improves with the addition of the uncontrolled burnt rice husk ash (RHAU) content until an optimum is reached, which more than that the strength begins to decline. The optimum RHAU is greater when the lime value is low, yet it is probable to reach higher UCS when a low amount of lime and high RHAU contents (more than the optimum RHAU related to high lime percent). This would be a more economical solution when commercial lime is used, since the RHA is a residue and very cheap [28,29]. Liu et al. proved that the RHA to lime ration of 4:1 can improve compressive strength of expansive soil 40 times, and 80 times its flexural strength if compared to lime mortar after 28 days of curing. Also, the decrease in swelling feature and swelling pressure amounts of stabilized soils is because of firstly to the addition of low-plasticity materials (lime and rice husk ash) and absorbent agent (RHA), and secondly because of the reaction between expansive soil and the RHA-lime additives. The active silica interacts with calcium ending in produce of calcium silicate hydrate (C.S.H) formation. Therefore, tested stabilized expansive soil turn out to be stiffer and more fragile than ordinary expansive soil. Authors mentioned four mechanisms acting together in stabilizing soil by mixtures of RHA and lime: 1. Stabilized Structure of RHA-lime, 2. Replacement, 3. Coagulation Reaction and 4. Ion Exchange. Besides, RHA-lime constrains expansion parallel to suppressing compression; in fact, the content of RHA-lime also decreases the compression index. Also, cohesion and internal friction angle of stabilized soil increase significantly when the mix percentages and curing time increase. Apparently, utilizing of RHA-lime has improved shear resistance of expansive soil, effecting positively its bearing capacity [30].

3.2.4 Sawdust Ash (SDA) (wood milling factories)

Near 10-13% of wood timber is turned to sawdust [39], and it is often stocked in landfills or used for burning in open-air. Researchers assessed the suitability of SDA as a subgrade soil modifier, which is a step forward lowering the amount of sawdust ash that subjected to landfills [26].

Several researches investigated the possibility of using SDA to improve the load bearing properties of different subgrade soils. Research was done combining SDA in various mix portions with diverse types of soils and it was seen that the geotechnical features of cohesive soils were altered. In their study, Butt et al. combined sawdust ash (0 to 12%) with subgrade soil with an increasing value of 4%. These experiments proved that at an optimum content of 4% sawdust ash, significant enhancement in the plasticity, specific density, unconfined strength and immediate CBR of the stabilized soils happens. The UCS increase up to 26% and CBR almost improved to the two times magnitude (Figure 6) [40].

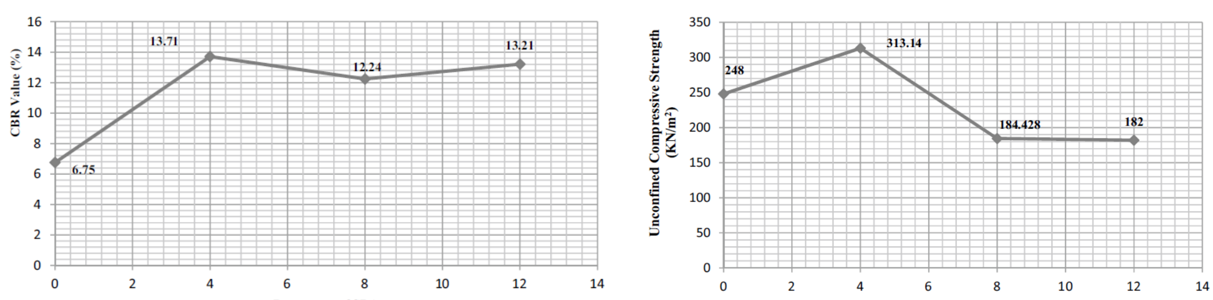

Figure 6. Variation of strength with addition of sawdust ash. Left: CBR, right: Unconfined compressive strength [40].

Khan and Khan demonstrated that the optimum reduction in permeability of a soil occurs when 12% SDA is added to it; strength parameters are also improved by increasing the quantity of SDA into the soil.

Furthermore, the dry density of the compacted soil with SDA was enhanced, and larger amounts of SDA are not desirable since the shrinkage of samples increase [39].
Ilori et al. demonstrated that soil mixture with SDA improves the properties of the virgin lateritic soil at optimum percentage of 12%. At this level of mixture, four times increase in strength of the soil as seen by UCS data, lesser expansion (showed by plasticity index of the resulting mixture) and lower values of plastic limit (than stale soil) were observed [41].

3.2.5 Groundnut Shell Ash (GSA)

Groundnut shell (Figure 7) is an abundant form of high-volume agriculture by-product broadly available in Asia. An overall land of 25 million hectares was planted with groundnut, producing more than 40 million tons of this product worldwide. The energy content of groundnut shells has introduced them as a source of biofuel for contributing the fuel of thermal needs with an order of 1.4×10^{11} MJ per year. Igniting these shells for discarding or energy generation aims is unavoidably followed by the generating of ash, the residue which can become an ecological issue in long term [42]. In the studies, utilizing GSA in structures has been investigated to decrease prices and improve strength, synthesize zeolite, absorbing pollutants, achieving silica, reinforcing rubbers and many composites, strengthening soils and bituminous pavements, concrete and bricks modification, together with active carbon production. By proving its economic, practical, and ecological compatibility, the pavement sector will be capable of utilizing huge amounts of GSA, in terms of an alternative solution to the disposal of this waste.
Some studies have been performed in order to utilize the GSA in concrete construction as fine aggregates replacement of sand [43,44]. In almost all studies, GSA showed negative effect on compressive strength of concrete despite reducing the density, which made the mixture suitable only for insulation as non-load bearing lightweight concrete.

Figure 7. Groundnut Shell and Groundnut Shell Ash (GSA) [42]

It is shown by Oriola and Moses that an addition of 4% is proven the optimum value to have highest amount of MDD and increase in UCS after 14 and 28 days of compaction, which are because of flocculation and agglomeration resulting volumetric decreases, voids filling within the coarse aggregate by GSA particles and time dependent strength gaining action of the pozzolanas. The rise in compressive strength is a result of enhanced hydration reaction by sufficient water. This is linked to the interaction between black cotton soil and the GSA to generate secondary cementitious phases. In black cotton soil at CSA percentage of 6, a maximum CBR value of 4.2% could be achieved which is usually considered not suitable for road applications [45].

3.2.6 Sugarcane Bagasse Ash (SCBA)

Sugarcane bagasse is achieved from crushing the sugarcane stalks for producing cane juice. It is consumed as boiler fuel for energy generation by the processing industry, which produce SCBA after burning. only India produces 90 million tons of bagasse every year and 8-10% of its weight turns to SCBA. Sugarcane Bagasse Ash, comparing to many other bio-waste generated ashes, has a light weight, a high surface area, less amorphous silica together with low carbon quantity (Figure 8). According to Kolawole et al. SCBA is one of the Supplementary Cementitious Mineral Admixtures (SCMs) that could be used for concrete pavements [46]. In fact, when sugarcane is burnt in boilers at high temperatures (600-800 °C) it can produce high amounts of SiO_2 and can be used as artificial pozzolana for the replacement of Portland cement [2]. Debbarma et al., in a study on many wastes to be used as cementitious minerals, showed that substituting SCBA by 10 and 15% in concrete, decreased the Compressive Strength, Split Tensile Strength and Flexural Strength, but improved the Cantabro Abrasion Loss [47].

Figure 8. Raw material of Sugarcane fiber and sugarcane bagasse ash (SCBA) [48].

Cordeiro et al. studied the SCBA for using as pozzolanic additive in concrete and clearly demonstrated that milling SCBA to dimensions of D_{80} (80% passing size) lower than 60 µm and Blaine specific surface areas higher than 300 m^2/kg, leads to products that could be categorized as pozzolans. This made possible the production of high-performance concrete with the same mechanical properties up to a 20% addition as the concrete made by just using Portland cement. Such addition of SCBA also caused increasing in rheology of concrete in the fresh state and resistance to attack of chloride-ions [49].

Onyelowe demonstrated that similar to other ashes, the addition of SCBA decreases MDD, while it causes increase in OMC. He showed a clear improvement in CBR adding the ash if compared to the natural soil. [50]. Similar phenomena was shown in a research by Reddy and Prasad, which reported a peak in CBR and UCS by the addition of 20% SCBA to a selected soil [51]. Kiran and Kiran observed that by the addition of SCBA to black cotton soil, the CBR and UCS values increased significantly with 8% ash despite no change in density was observed. However, a blend of SCBA and cement in different portions could make an increase in density with a peak at 8% SCBA and 8% cement. The CBR and UCS values both got increased double for addition of 4% bagasse ash with 4% lime. So authors believe that SCBA should be used in combination with lime and cement for soil stabilization purposes, as the difference in performance is considerable [52].

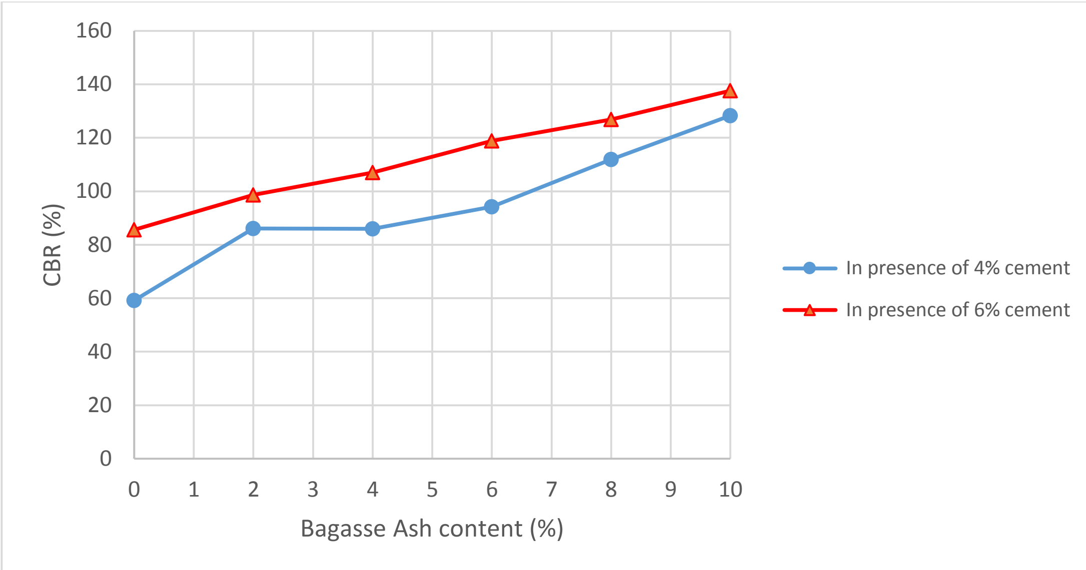

Figure 9. California Bearing Ratios of lateritic soil with partial replacement of SCBA [50]

Kumar Yadav et al. studied rural roads stabilization of alluvial soil for subgrade using SCBA together with two other recycled bio-waste ashes. Similar performance trends of mixes with other ashes were observed for SCBA mixes: for a medium plasticity soil, the addition of the stabilizing agents lowered the maximum dry density, while it raised the optimum moisture content regardless of the stabilizer type. The amount of unconfined strength and immediate CBR of soil increased by 80% and 27.0% respectively by addition of 7.5% SCBA, which is less than increase caused by the RHA used in the same research. These stabilization by various kinds of bio-wastes can lead to reconsidering the design thickness of layers in the pavement structure (Figure 10)[53].

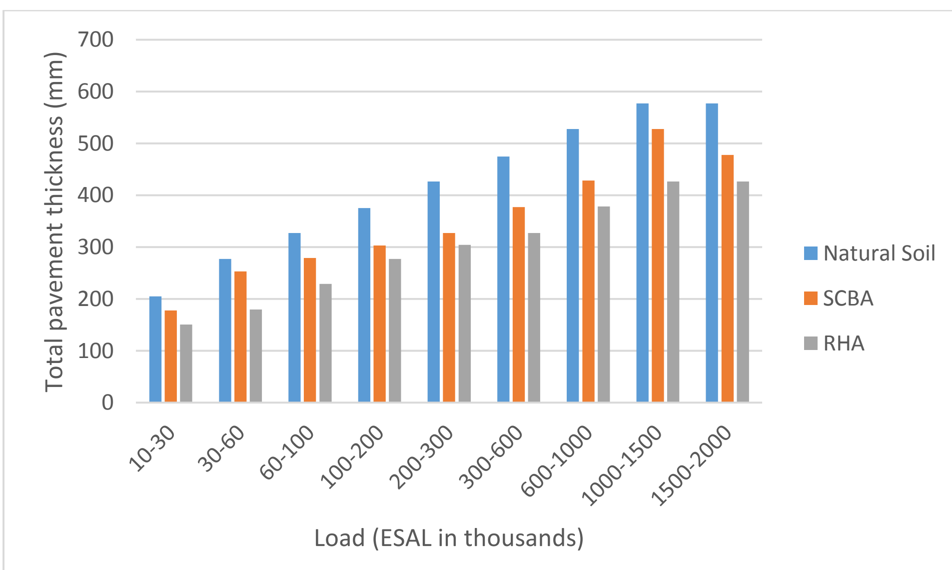

Figure 10. Decrease in layer thickness of pavements by stabilization with addition SCBA and RHA [53].

Jamsawang et al. also investigated the optimum blend of SCBA and Portland cement and demonstrated that the correlation between the elastic modulus and the unconfined compressive strength can be shown as a linear function. They showed that the 20:80 SCBA to cement ratio would give a peak in elastic modulus and unconfined strength (q_u) of clay soil in both soaked and un-soaked conditions. Despite initial serious strength loss for all combinations, the optimum blend showed the minimum loss. The variations of the modulus of elasticity (here measured at 50% of the ultimate strength q_u for ease of calculating: E_{50}) with curing time and CBA amount is very coherent with the growth of q_u in the considered materials. As a result, a numerical correlation potentially exists between q_u and E_{50} [54]. Therefore, these fitting curves (Figure 11) are beneficial for estimating the strength behavior of SCBA mixes, leading to providing engineers with a improved design of the proposed stabilizing solution.

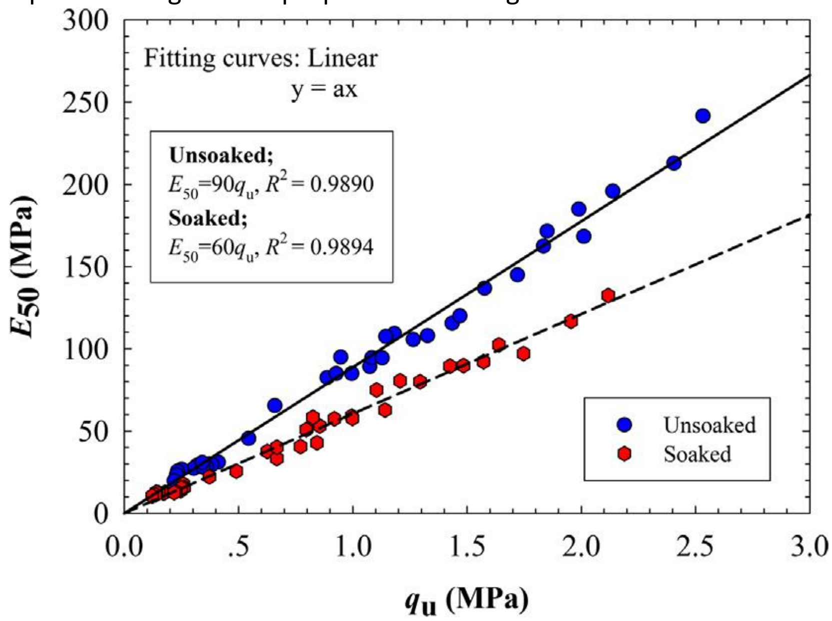

Figure 11. Correlation between elastic modulus and strength in clay soils stabilized with SCBA and cement [54].

3.3 Stabilizing with recycled powders from crushed bio-wastes

3.3.1 Eggshell powder (ESP)

Egg shells are generated from food industries, hotels, restaurants, etc. in massive amounts and recently they are facing disposal challenges [55]. The chemical composition similarities of lime and eggshell powder suggests the possibility of using the ESP to substitute lime in soil stabilization methods. Eggshell powder was previously studied also as partial replacement of Portland cement in concrete [56]. It is shown by Ramli et. Al that as the fraction of eggshell powder increases, the optimum moisture content will raise and the Maximum Dry Density value will reduce. The reverse change in OMC and MDD is a consequence of the addition of ESP, the surface area of the particles is enlarged, which demands more water to cover the entire matrix of the mixture to allow the chemical hydration reactions and exchange phenomena that cause improving strength. A 3% of ESP binds the soil particles due to addition of lime, particularly in soaked conditions. Indeed, this recycled waste was discovered to be potentially reactive as additive to the foundation soils to increase its load bearing values [57]. In a study by Johns et al., it was shown that eggshell can effectively replace lime and mixed with soil up to 12% in weight. Also, the compressive strength of clays improves with the addition in lime percentage up to 6% used with 12% ESP, and then the value decreases with further addition of lime [58]. Also, in another research by Anoop et al., it was shown that ESP can replace up to 25% of the lime utilized for stabilization processes. This substitution improved the strength of the treated soil, too. Therefore, it can be inferred that ESP is a valid powder to replace lime in stabilization of soils up to a certain amount, thanks to their similar chemical compositions and properties [55].

Table 4. The chemical composition of Eggshell Powder.

Oxide	Pravin Kumar et. al [57] (%)	Ramli et. al [56] (%)
CaO	50.7	60-67
SiO_2	0.09	17-25
Al_2O_3	0.03	3-8
MgO	0.01	0.1-4
Fe_2O_3	0.02	0.5-6
Na_2O	0.19	0.4-1.3
SrO	0.13	-
SO_3	0.57	1.3-3
P_2O_5	0.24	-

3.3.2 Crushed Coconut Shell (CCS)

The crushed coconut shell has been considered a potential stabilizer for soils as well, due to its good stability, abrasion resistance and toughness [11]. It is of because of good weather resistance of coconut shell as it is considered appropriate to be selected as construction material [20]. In a study by Ramli et al., it is shown that the addition of grinded crushed coconut shell to the laterite silty sand soil rises its OMC and reduces its maximum dry density. This increment in OMC value is because CCS has excessive humidity absorption and can be used as alternative of traditional aggregates with no further surface treating. Also, in the form of powder, the surface area of the fines is increased which demands more water to cover the entire matrix of the blend to fulfill the chemical reaction of hydration and exchange processes that ends to the improve in bearing capacity of the mix. Based on the obtained CBR results, it is proven that optimum addition value of 4% CCS into soil gives best outcome in soaked and un-soaked conditions [21].

In a study by Salih et al., it has been shown that the creation of a CCS layer through the depth of the specimen showed meaningful change in CBR values. It is seen that the presence of CCS dispersed in soil, can improve the CBR value up to the 4.8 times. More increase is possible with two layer distribution , but since the CBR increase ratio per CCS consumption weight unit, a single layer inclusion is more cost efficient. The optimum size of CCS is 1 cm, which provides 16.2% of CBR improvement per unit weight of added CCS that is the most cost effective value (Figure 12) [10].

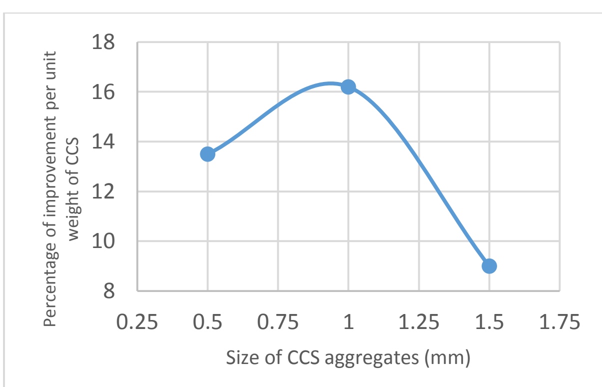

Figure 12. Increase in CBR per unit used CCS mass of several sizes [10].

These results were confirmed by Ranjitha et al., it was shown that the bearing capacity of black cotton soil become better by the inclusion of CCS. The tentative investigations gave a clear explanation of effect of CCS on increasing CBR values for the treated soil. (Figure 13) [11].

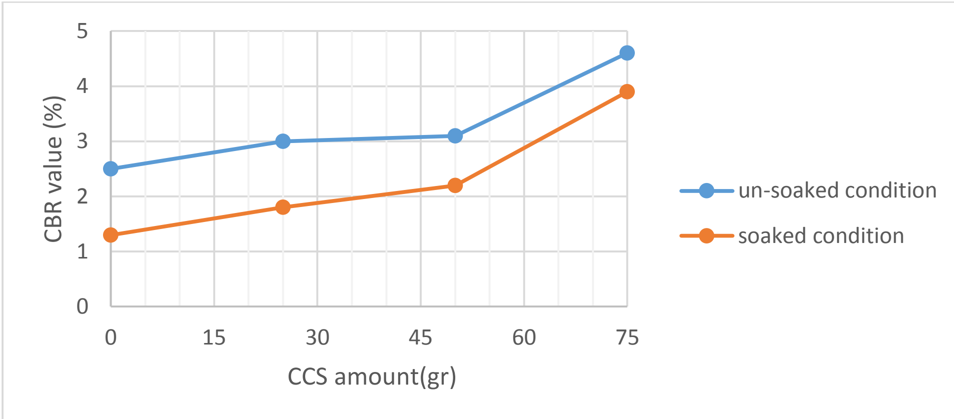

Figure 13. Effect of inclusion of CCS on the top layer of proctor compression on CBR values [11].

3.3.3 Seashell powder

Seashells are the oceanic bio-waste originated from the sea shores and they can be utilized as filler after washing and effective crushing. It consists of high quantities of CaO, which can form strong adherence with bitumen and make the mixes more resistance to moisture. Seashells have a jagged surface texture which can higher the optimum binder percent of the mixes [2]. The general researches show that seashells can be utilized as aggregate substitution , but their salt presence and chloride ion content can be destructive to asphalt or concrete mixes [59]. Moreover, the occurrence of chemical reaction of CaO, SiO_2 and Al_2O_3 together with water during the addition to soils in large extents, could cause a good like between seashell ash and soil particles. Ca ions of the soil enter in a pozzolanic reaction with Al and Si ions of the ash ending in formation of Calcium Aluminate Hydrates (CAH) and Calcium Silicate Hydrates (CSH) [26]. It is shown that 99% of crushed seashell particles were flat (Figure 14). In a research that applied crushed seashell (CSS) in sandy subgrade soil, an improve in the soil maximum dried density is reported by 45% addition of CCS, while beyond 45% of CSS reduces the maximum dry density of natural soil. In all cases, lower water percent is needed for compacting the soils, which could be due to decrease in the fines fraction. Being flat, the particles of CSS are large enough to permit satisfactory mobility among the continuous sand matrix. Addition of more than 45% of CSS particles causes more voids, needing more sand to fill the spaces between the particles, resulting in a decrease in density. Inclusion of CSS in natural soil results in a better density than using less water with the same compaction energy. This is an important point for compaction operations in dry weathers where moisture sensitivity is a challenge. The CSS addition increases the CBR of natural soil. It is shown that the specimen with 45% CSS addition results CBR value of 121%, higher than 51% for the CBR of compactions with no CSS (Figure 15 b) [59].

Figure 14. Flat particles of CSS created after crushing seashell [59].

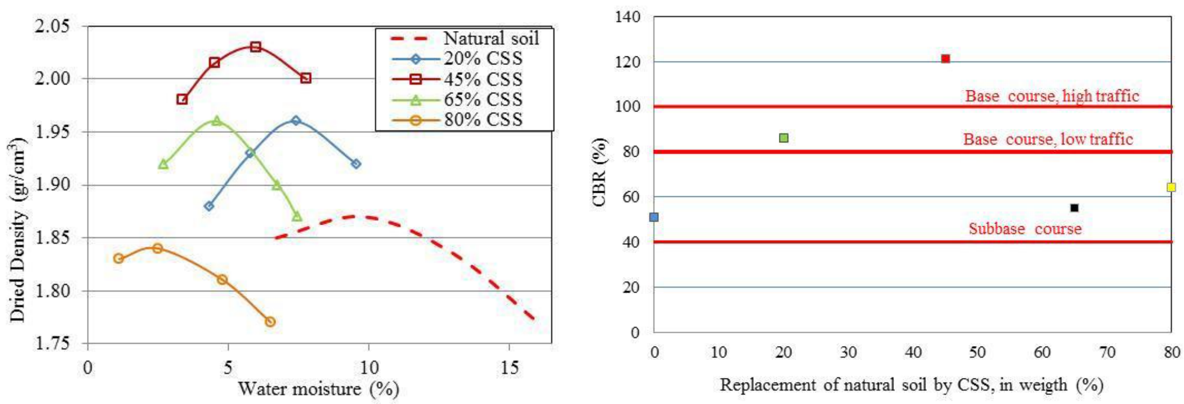

Figure 15 a. Influence of soil replacement by CSS on compressibility. b. Effect of CSS replacement on CBR of natural soil [59].

4 Recycling bio-waste as asphalt binder additives

4.1 Recycling as filler (less than 0.063 mm)

In the face of being utilized in limited content, the filler addition in asphalt concretes is substantially effective. Many features of mixes can be change by fillers, such as mechanical strength and volumetric proportions, reducing optimum bitumen content, stiffening the bitumen, improving the resistance against permanent deformations at elevated temperatures, resistance to low temperatures cracking, besides fatigue strength. Fillers also influence cohesion in the aggregate-bitumen matrix, which controls moisture sensitivity of mix, affecting aging process of asphalt mixes by either catalyzing oxidation or by blocking the diffusion of oxygen in mastic, modifying thermal functioning and altering constructability by affecting mixing and compaction temperature of the mix [2].

4.1.1 Groundnut Shell Ash (GSA)

The main chemical constituents in GSA are CaO and SiO_2 [41]. There are limited number of studies indicating the utilization of GSA as filler. In one of these researches on modified asphalt binders, Arabani et al. reported ductility and softening point variations together with altering penetration grade prior aging by adding GSA as shown in Figure 16. It is obvious that by addition of GSA in the asphalt binder, ductility and penetration grade reduced and softening point improved. It was shown that increase in ash content enhance the variation between the softening point of the upper and lower parts (ΔS) of the samples [42].

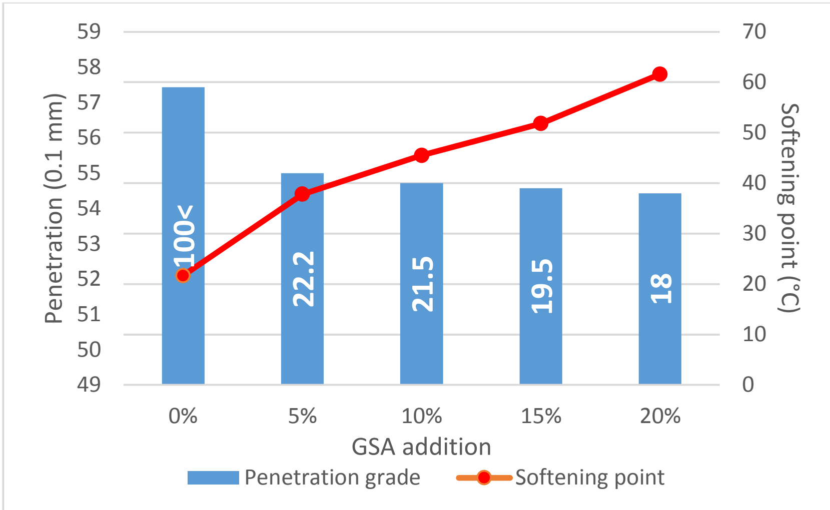

Figure 16. Rheological features of asphalt binder (based on ASTM D5, ASTM D36, and ASTM D113 standards) treated with GSA. The numbers inside bars are the ductility of mixes (cm) [42].

4.1.2 Rice Husk Ash (RHA)

In parallel to the applications of the RHA as soil stabilizer, it is demonstrated that RHA at 50% limestone filler addition content, gave to hand bituminous mixes with enhanced Marshall stability and volumetric attributes. The ash particles effect the binder by increasing its cohesion and stiffness resulting to improvement of the mix Marshall property. Besides, RHA treated asphalt concrete mixes have elevated permanent deformation, moisture damage resistance, cracking and aging during time as in comparison to mixes with fillers of hydrated lime or cement. On the other side, it was proven that the porous essence of these ashes can have destructive influence to the functioning of bituminous asphalt mixes in means of moisture susceptibility, stability, rutting resistance and fatigue cracking contrasted to usual mixes with stone dust filers [2,24]. Han et al. reported that the replacement of RHA in base asphalt can radically advance the elevated-temperature performance. In this research, 1% RHA by weight was proved to be the optimum percent for modification of 70# (JTG F40-2004) bitumen and 7% was shown as the maximum addition limit for compatibility requirements through hot mix asphalt compaction. Conversely, RHA modified asphalt mixes have insufficient low-temperature and fatigue resisting features, significantly restraining its utilization in pavements. Assumed crisscross network of irregular flakes and micro-pore nature of RHA shown in Figure 17 could be the main reasons why modified asphalt can reach excellent high-temperature performance. [60].

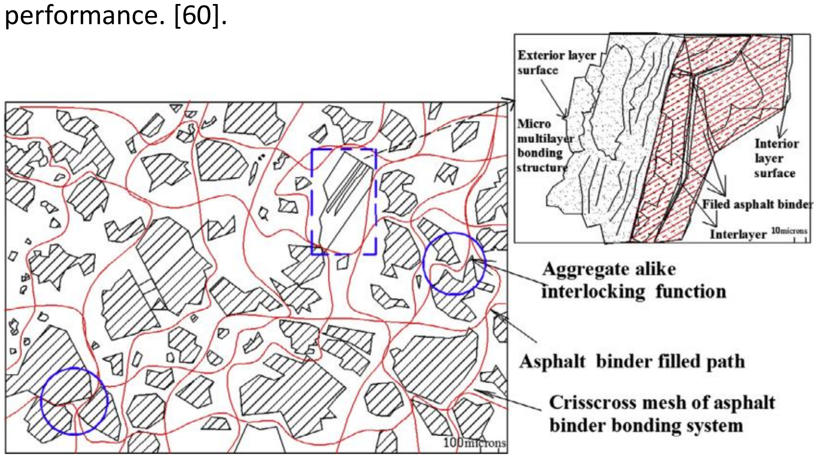

Figure 17. Demonstrative representation of the bonding network between rice husk ash and mix [60].

Sargin et al. tried to identify an optimum value for RHA filler content and the proportional bitumen amount for this filler quantity. It was suggested that an optimum of 5.0% of RHA and 4.7 % of bitumen would provide best results in terms of stability, bulk specific gravity, air void percentage and Marshall stability. This work showed that RHA can be successfully applied as a binder filler alternative to limestone in common hot mix asphalts [24]. Arabani et al. also displayed that the results for rheological features of bitumen were improved by adding RHA. They reported that the rise in RHA percentage headed to an elevation in softening point and decrease in penetration of bitumen, leading to have stiffer asphalt binder. Moreover, like most of filler, also the addition of RHA made the adopted asphalt binder more viscous. Also, Penetration Index (PI) was improved with adding RHA amount that made a decrease in thermal susceptibility of the bituminous binder. They also showed that the use of RHA, up to 20%, in those asphalt concretes could improve their stability. Besides, Marshall quotient as an indicator of rutting feature of asphalt mixture was improved by the addition of ash. Finally, the improvement of fatigue life might be because of air voids content reduction in the mixture and the enhancement of adhesion between binder and aggregates, either. Based of fatigue life diagrams of mixes with different RHA filler contents shown in Figure 18, the authors reported that the RHA addition of 15% had the best fatigue resistance [61].

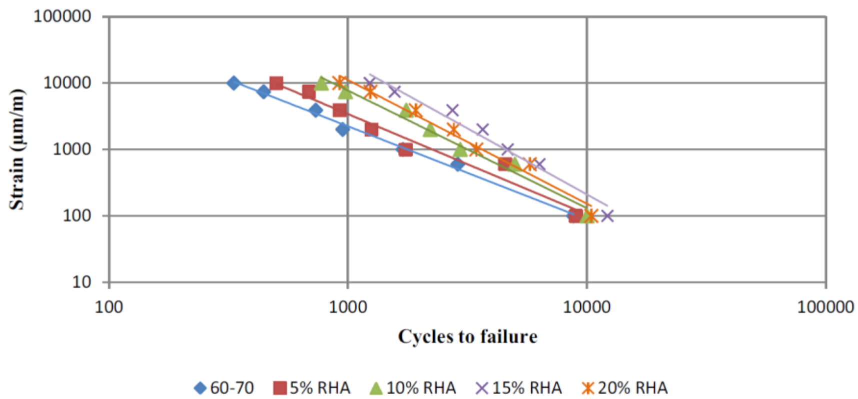

Figure 18. Fatigue life of asphalt mixes with various amounts of RHA filler [61].

4.1.3 Sugarcane Bagasse Ash (SCBA)

Due to the low specific gravity of SCBA, it can occupy large volumes, thus requiring special care particularly when used in non-dense graded blends like stone mastic asphalts. In general, The bituminous asphalt mixes enriched with sugarcane bagasse ash as filler have limited enhanced Marshall parameters, with an considerable elevation of resilient moduli results comparing to regular asphalts [2]. Zainudin et al. also evaluated the effect of SCBA as filler in Hot Mix Asphalts (Table 5). They showed that bagasse ash was effectual in improving Marshall stability, flow and Resilient Moduli of standard Hot Mix Asphalts (HMAs). For a conventional hot mix asphalt, the SCBA causes 0.6% increase in Marshall stability, 5% in flow and 17% in Resilient Modulus respectively. Therefore, they declared that SCBA has potential in modifying common HMA with an optimum value[48].

Table 5. Comparing common and SCBA modified hot mix asphalts [48].

Characteristics	ordinary HMA	Modified Sample (SCBA)
Density (g/m³) [ASTM D70]	2.33	6772.31
Total voids in mix - VTM (%)	4.11	4.94
Asphalt filled voids -VFA (%)	75.18	71.41

Stiffness (kN/mm)	7.06	6.77
Stability (kN/mm)	24.63	24.79
Flow (mm) [ASTM D1559]	3.49	3.66
Resilient Module (MPa) [ASTM D4123]	2298	2697

In a similar research, Rachman and Tanijaya evaluated the replacement of hot mix asphalt filler with SCBA in various layers of asphalt concretes. They showed that adding higher quantities of SCBA as filler, overall volume of air-voids in compacted asphalt decreased, which is a reverse trend of increasing voids filled by bitumen (Figure 19) which could be due to the "cavity filling" function of SCBA. Higher proportion of SCBA substituting standard fillers will cause more value of voids filled by bitumen (VFB), because bagasse ash will fill cavities, especially between aggregate particles in the mixture [62].

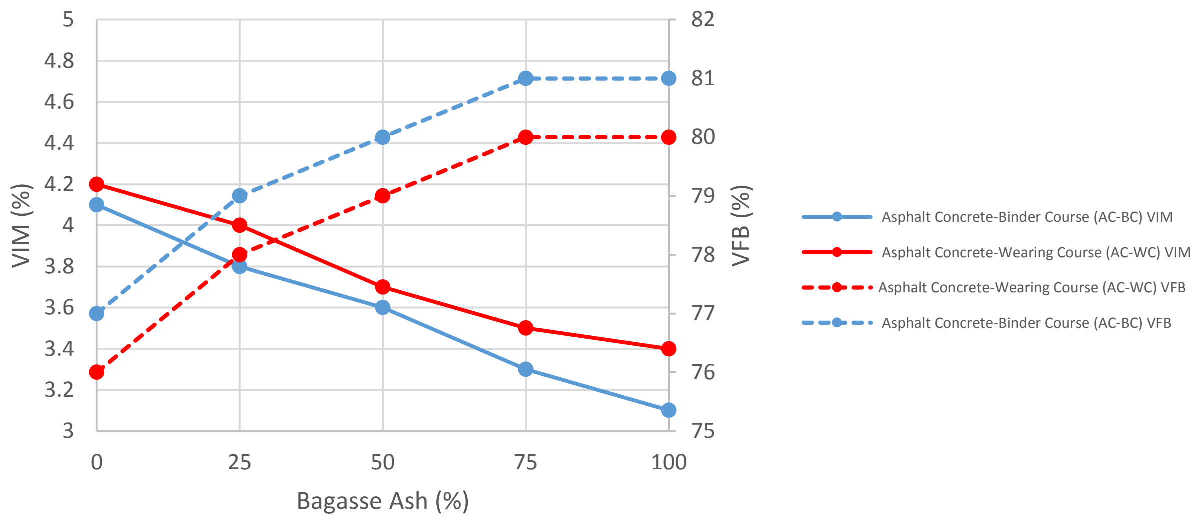

Figure 19. Correlation of voids In the compacted Mixture (VIM) and voids filled with bitumen (VFB) with SCBA addition [62].

4.1.4 Palm Kernel Shell Ash (PKSA)

Similar to utilizing the PKSA as soil stabilizer, there are some limited studies of application of this ash as filler. In a study by Nwaobakata et al., the ability of PKSA as filler to enhance the rutting and fatigue resistance of Hot Mix Asphalt, as well as the moisture sensitivity was subjected to research. They demonstrated that there is an optimum content value for the percentage of PKSA for achieving the best performance of filler in terms of flow and density. Compared to the control mixture, the filler addition 3% by weight of total mix lead to highest performance for stiffness, fatigue and resistance to permanent deformations ; on the other hand , some mechanical properties of the same mix were shown as improved when the filler content exceeded 3% in weight. PKSA filler mixtures showed significant increases in fatigue life and moisture resistance, indicating good relationship between fatigue life and permanent deformations [63].

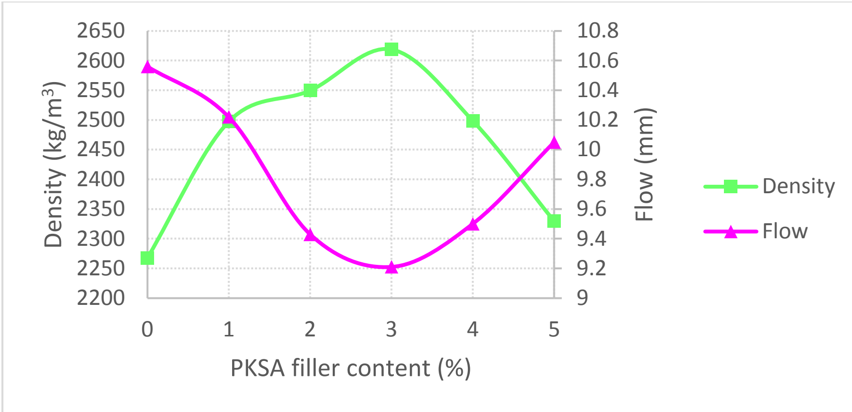

Figure 20. Graph of Flow and Density vs. amount of PKSA [63].

4.2 Activated Carbon

Utilizing activated carbon powders gained from residues as a bitumen modifier or additive would be useful considering environmental impact, mechanical features and costs. Activated carbon is generated from carbonaceous base materials like wood, coconut husks and coal. Besides, vinasse, marc and hazelnut shells are some of the available sources of bio-waste materials utilized to obtain activated carbon while distillation alcohol from molasses. The application of activated carbon in bitumen makes them more stiff having better function in high temperature of bituminous mixtures.

Seyrek et al. studied the influence of adding activated carbon to the bitumen on various rheological properties of the bitumen and mechanical characteristics of hot mix asphalts. As expected, the penetration value of the binders decreased, as the enhancement in softening point and viscosity. Also, Dynamic Shear Rheometer (DSR) test proved that bitumen binders' deformation (rutting) resistance was improved with the using of activated carbon. While the stiffness improved as the additive content enlarged, modified binders had similar low temperature performance to the neat binder. Moreover, the tensile strength results improved unceasingly during modification before conditioning with addition of activated carbon to bitumen. By conditioning, tensile strengths of the modified mixes reduced, which indicated the decreased the damage induced by resistance to the moisture. Authors suggest that this could be happen by the hydrophobic form of activated carbon, as it has an organic origin.

Adding activated carbon to bitumen for modification of HMAs considerably improved the indirect tensile stiffness module and fatigue resistance. Furthermore, as a matter of creep test, the resistance of mixes against permanent deformations significantly increased. The authors concluded that all the properties of mixes improved except only for the resistance to moisture-induced damage [64].

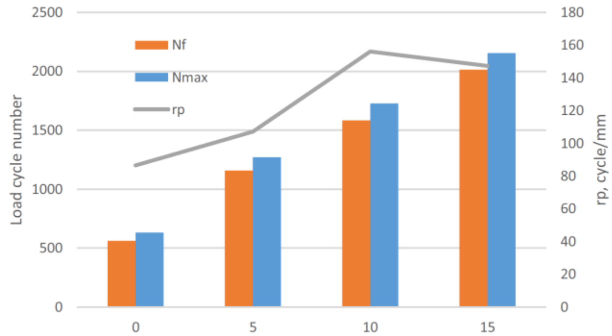

Figure 21. Variations in maximum load repetition count (N_{max}), fatigue cycles (N_f) and rate of Crack propagation (r_p) with the activated carbon additive content in hot mix asphalts [64].

In another study by Bostancioğlu et al. the effects of two types of active carbon from bio-waste (obtained by vacuum pyrolysis of hazelnut shells) and industry (furan resin) were compared as binder additives. It was shown that the optimum binder content and stability value in hot asphalt mixes increased by using active carbon obtained from both sources, but the Marshall stability values of bio-waste active carbon modified mixtures declined with the rise in active carbon percent. The Marshall quotient and resistance to permanent deformation increased by adding active carbon to bitumen binder because of decreased flow rate despite higher optimum binder content values. Moreover, the ITSM numbers of active carbon modified mixtures are higher than that of the original mixture and regularly decreased with the increase in carbon content. Also, the indirect tensile strength magnitudes of both dry and wet mixtures growth with the increase in modifier content and the indirect tensile strength ratio of modified samples increases by carbon content (Figure 22), but they could not reach the common threshold of 85% for layers of major roads [65].

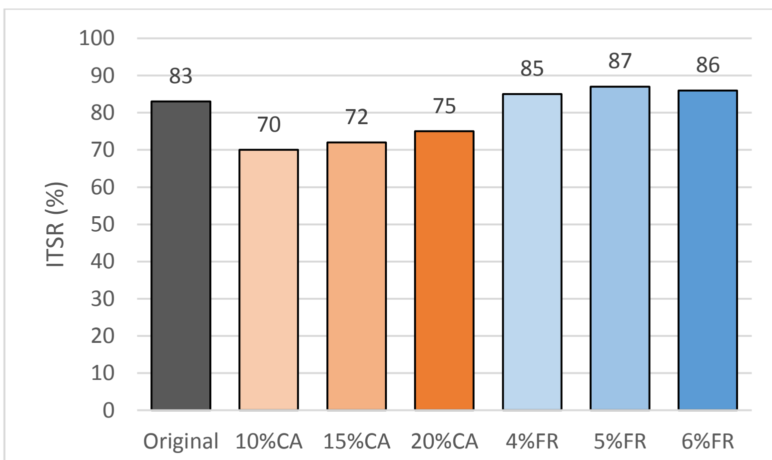

Figure 22. ITSR variations for HMA samples with active carbon added bitumen. CA: bio-waste based active carbon, FR: furan resin obtained active carbon [65].

5 Review outcomes and conclusions

This article aimed to provide a comprehensive review on the use of different bio-wastes obtained from agricultural activities, as pavement engineering materials. In fact, agricultural by-products are one of the main categories of solid wastes from human activities worldwide. In highly populated agricultural countries, part of these wastes can be successfully employed for paving and maintaining rural and low traffic roads. These applications would lead to considerable steps towards the sustainability of road

construction, mainly because this recycling will hinder large amounts of waste materials to be landfilled. Hence, a rising demand for alternative resources that can substitute traditional aggregates, soil stabilizers and fillers in the pavement construction and road maintenance has been seen in recent decades.
The researches included in this review have identified positive impacts of the studied wastes on several aspects of traditional paving solutions. While the applications of the aggregate, powder and textile forms are limited to some specific types of sources and products, the use of ashes is more widespread and, as a result, it has been more investigated. This could be due to the fact that making heat from burning bio-wastes having hydrocarbon nature is also a convenient method for generating energy in many developing countries. The resulting ashes can be used as filler for bituminous mixtures, but they are mostly used to strengthen weak soils. For instance, ashes from different by-products of residues of rice husk, palm, sawdust and nut shells have been successfully used in soil stabilization process with or without additional cement. In fact, the chemical reactions of materials in form of ashes could contribute in strengthening soils. This is even more eco-friendly when considering that these ashes could reduce the amount of common cementitious additives by joining the chemical reactions of hardening. This highlights the need for chemical reactivity of the ash's constituents, which are usually rich of alumina-silicates. The application of agro-residue wastes and by-products in bituminous mixtures has been proven to be feasible and often very effective. The available powders are usually seen as binder additives (fillers) or modifiers and contribute to the rheology of the bitumen first and consequently of the asphalt concrete. There are usually limits in the incorporation of these fillers into bituminous mixes and these are mainly related to the potential water damage induced by the new fillers and by the absorption of binder to form the binding mastic.
The number of past and present research on these wastes to be used in paving applications describes the increasing interest on them and the potential benefit that the industry of roads can have, especially where resources are lacking and these wastes are often abundant (i.e. developing countries). The existing outcomes reveal the peculiarity of those materials and the fact that they can be used in different ways in paving materials, having different effects on the final properties of the constructed layers. Indeed, the specificity of their use and the actual combination with the available materials (soils to be treated, binders to be modified) requires testing programs to support the proposed application.
The substitution of non-renewable resources with the described agricultural wastes seems to be one of the potential valid solutions to a number of disposal issues worldwide, thus contributing to the carbon neutrality of the paving industry.

Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper, which may be considered as constituting a real, potential or apparent conflict of interest.

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CHAPTER 3: FULL LABORATORY ASSESSMENT OF CDW RECYCLED AGGREGATES FOR SINGLE OR MULTI-LAYERED RURAL PAVEMENTS

FOREWORD

The objective of this chapter is to investigate the physical and mechanical properties of a collection of selected individuals and combined recycled aggregates. In general, the recycled aggregates were used in batches with similar homogenous aggregates or with dissimilar aggregates from different materials (combined). This, together with many other parameters, have tremendous effect on the physical and mechanical properties of compacted specimen and/or road layers made with these materials. Both classes of materials were used for laboratory investigations in this chapter.

At first, the introduction describes the different types of recycled aggregates selected to be applied in pavement layers in unbound and cement-bound conditions. Next, the chosen aggregated have undergone a wide range of testing procedure including those related to the effect of paving operation, such as fragmentation during compaction. The outcomes are analysed by considering the possible mechanisms that makes the results of tests on blended aggregates mixes differ from the average value of individual constituents. The results and discussions are focused on the prediction of the behaviour of blends in real pavement layers. One of the main investigated issues of simple (one or two layers) pavements in low-traffic rural roads is bearing capacity and its persistence in time, along with the possible environmental concerns related to the potential leaching of contaminants coming from the recycled materials. For these purposes, the assessment of the material's mechanical behaviour and a comprehensive chemical and environmental leaching analysis are performed. From the results, a through representation of properties of the selected mix of aggregates is shown, and eventually some conclusions have been made showing the suitability and limitation of utilizing these materials in various layers of low traffic roads and other farming pavements.

The research presented in this chapter has been described in the following journal paper:

Pourkhorshidi S., Sangiorgi C., Fathollahi A., Coupe S. J., Torreggiani D., Tassinari P., Laboratory compaction and leaching assessment of recycled aggregates for unbound pavement layers. Road Materials and Pavement Design (under review), submitted 2023.

Authorship declaration

A summary of each author's contribution to this work is provided below.

Conceptualization:	S. Pourkhorshidi, C. Sangiorgi
Writing – original draft preparation:	S. Pourkhorshidi, A. Fathollahi
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Laboratory compaction and leaching assessment of recycled aggregates for unbound pavement layers

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Abstract. Various recycled materials obtained from civil engineering activities have been tested to be used in different pavements layers, from the emerging circular economy perspective, towards the construction and maintenance of greener roads. Up to now, Construction and Demolition Waste (CDW), Recycled Concrete Aggregates (RCA) and Reclaimed Asphalt Pavement (RAP) have been widely investigated worldwide for their application in unbound layers of pavements, while other types of recycled aggregates such as Crushed concrete railway sleepers (TRV) are being considered for more specific applications due to their mechanical strength. In this research, a set of laboratory physical and mechanical tests along with leaching assessments have been done on recycled aggregates obtained from civil engineering activities. The materials have been provided by a certified recycling plant and their performances have been compared as potential sustainable materials for unbound layers of pavements. Moreover, two materials were also tested for cement bound layers. It was found that, despite the overall quality of the selected aggregates, the performance of materials could vary to a large extent as the properties of recycled mixes are highly dependent to their constituents. Still, most of these high-quality materials pass the thresholds of local specification and they can be applied in unbound layers of pavements. In parallel, the results of horizontal dynamic surface leaching tests (DSLT) revealed that the release of hazardous substances including heavy metals and trace elements from ASFC (Stabilized mix of Crushed concrete and Reclaimed asphalt), CDW and RCA were far below the EU Water Framework Directive limits and their possible application in road construction was safe.

Keywords: *recycled aggregate; pavement materials; leaching, compressibility, sustainable pavements*

INTRODUCTION

Each year large amounts of solid waste are generated all around the world and require persistent research on their recycling, in order to preserve the ecological stability of planet earth and turn human activities, including transportation, to be more environmentally sustainable [1–4]. The largest part of these solid wastes is generated from construction and demolition of different civil engineering structures, such as concrete and masonry buildings, asphalt and concrete pavements and other concrete-based structures [5]. Today, the need for state-of-the-art and sustainable materials for different chains of construction activities is high and it is continuously increasing due to the visible effects on climate. The environmental concerns related to the depletion and excavation of non-renewable materials, as well as the high cost of procurement of virgin construction materials are today major leverages towards improved recycling [6].

In recent years many studies have been completed on utilizing recycled aggregates of civil engineering activities in pavement layers [7–13]. As an example, Barbudo et al. evaluated the effect of composition of RCA on its mechanical behaviour and physical properties. The author demonstrated that, despite the high expected influence of the components on the mechanical behaviour of recycled aggregate, the complexity of different mechanisms limit the estimation of the blend characteristics by just correlating to the properties of each constituent. Therefore, the results of each mechanical test cannot be accurately estimated from the constituents obtained in the composition test, and needs more attention to the interaction of aggregates from different sources. So, the constituents of recycled aggregates obtained from the composition test alone do not explain the mechanical behaviour of their blend [14]. Also, Del Rey et al. reported a case study on the use of CDW materials for low traffic pavements, and they recommend the adoption of RA in unpaved rural roads with low traffic, which resulted in acceptable deflection values, despite the high percentage of masonry waste could lower the mechanical properties of these recycled materials [15].

Besides, construction materials can trigger severe environmental concerns when in place and when replaced at the end of their life [16,17]. In fact, although it is desirable to recycle waste construction materials to achieve sustainability in road construction, there is a gap of knowledge on their environmental performance when used in unbound granular layers of road pavements. It is known that road pavement materials are regularly exposed to rainfall and road runoff, thus physical and chemical conditions of the runoff in contact with road pavement may facilitate the release of hazardous substances from waste materials available in the structure of pavement [18]. The chemical properties or in other words, the presence of pollutants in waste materials, are not usually the main consideration in environmental suitability of road materials, but it is important to evaluate the contamination release capacity of any material proposed to be used in certain standard conditions [19]. It is also important to remember that laboratory results from environmental evaluation of waste materials should not directly be applied to construction site, due to fundamental differences in aggregate compaction, contact time with water, temperature and other factors [20]. For this reason previous studies have evaluated methods to relate the results from leaching experiments based in laboratory and construction sites to one another [21,22].

Various standards have been established and proposed by regulatory bodies in Europe and the US regarding the release of hazardous substances from construction materials including CEN/TS 16637-1:2014 [23], EN 12457-4 [24], NEN 7343 [25], CEN/TS 14405 [26], EN 14997 [27] and TCLP 1311 [28]. The cited methodologies and quality standards have been utilized by various studies in the literature to evaluate the leaching behaviour of construction and building materials [21,29–33]. As an example, Butera et al. by investigation on several batches of CDW wastes in two studies, showed that polycyclic aromatic hydrocarbons (PAHs) and polychlorinated biphenyls (PCBs) can make concern in CDW materials, and some elements such as Cr, Se, Sb, and component like SO4 in runoff flow over these aggregates can reach above the EU limitations of wastewater and inert waste for landfills [34,35]. In parallel, Gupta et al. showed that many hazardous elements ha very close to threshold amounts in leaching test of RCA, which are higher than amounts related to traditional natural aggregates (Lime rock). Moreover, the pH level can be raised to above 10 which makes the run-off water more risky for sensitive environments [30]. As a result, more in depth analysis should be considered while utilizing these aggregates for farming and agriculture ecosystem.

OBJECTIVE

Many technical aspects such as feasibility, sustainability and durability under severe traffic and weather conditions were evaluated in different researches on recycled aggregates. Like all common and traditional materials used for construction and maintenance of pavement layers, before being actually used, recycled aggregates mixes need to be evaluated in terms of strength, load-bearing capacity, compactability and chemical stability. Despite the numerous studies mentioned above, a comprehensive assessment of the characteristics and performance of recycled aggregates from a wider range of sources (e.g. railway sleepers) cannot be found in the literature. The proposed research aims to determine how the type and composition of recycled materials, according to EN 933-11, can affect the mechanical behaviour of recycled aggregates (fragmentation, compaction and bearing capacity) by means of analysis and estimates of correlations. For this purpose, certified Italian recycled materials were assessed in terms of gradation, constituents, fragmentation, compactability, bearing capacity and leaching of chemicals. The main goal was to evaluate whether these materials could be categorized as “high-quality” ones and adopted for different pavement layers, in particular for unbound layers, in comparison to conventional materials and the existing specifications. Moreover, the leaching behaviour of ASFC, CDW and RCA were evaluated according to the European Commission CEN/TS 16637-2 [23] standard at a laboratory scale. The results from CEN/TS 16637-2 leaching tests can be used to estimate the release of substances in construction site conditions. The results of batch leaching tests are presented and compared with the EU Water Framework Directive limit values to evaluate the safety of their application in road unbound granular layers.

MATERIALS

The studied materials are five different products of an Italian recycling plant (located in Imola, Province of Bologna), which produces certified recycled aggregates for construction purposes. These materials are listed in Table 1 and shown in Figure 1. All the materials have European certificates and are in the range of 0-30 mm particles' size. Three out of five materials have a well-graded granular distribution, which makes them suitable for being used in pavement applications. The amount of floating elements in the supplied materials are very small. For each material, a sample of 100 kg was obtained from the recycling plant.

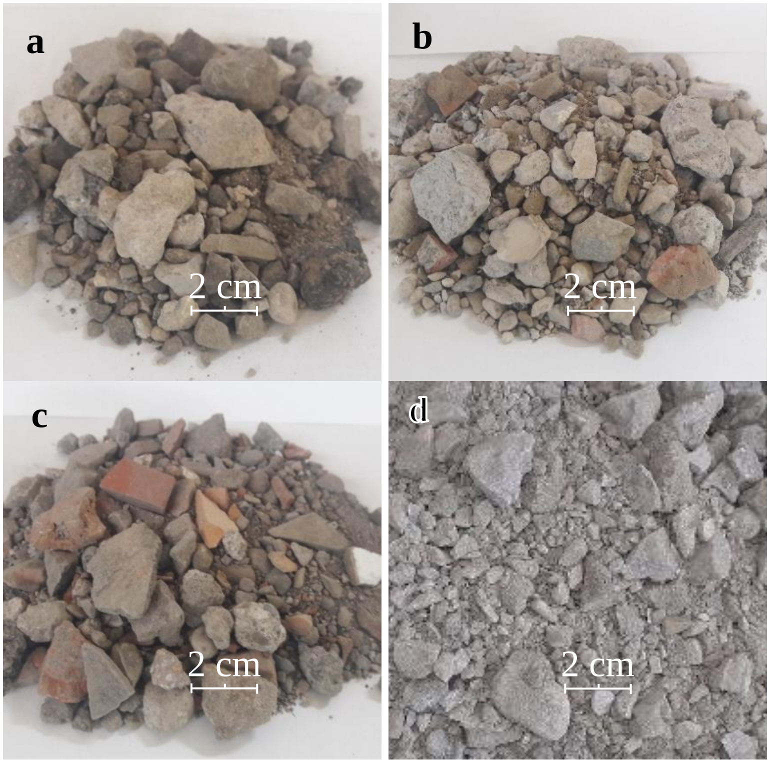

Figure 1. The recycled materials. Top left: Stabilized mix of Crushed concrete and Reclaimed asphalt. Top middle: Stabilized Recycled concrete. Top right: Construction and Demolition waste. Bottom: Stabilized Crushed concrete sleepers.

The waste materials were collected from construction and demolition sites in the area of Imola and delivered to the recycling plant for their processing. The foundry waste was brought from steel industries located in a range of 200-300 km from the plant, while the concrete railway sleepers were collected from the national rail network maintenance works in the area of Bologna.

Table 1. Composition of recycled materials used in the research.

Material	Containing	Composition	Abbreviation
Stabilized mix of Crushed concrete and Reclaimed asphalt	- Concrete-based building demolition rubble: industrial floors, beams, pillars, etc. - Vineyard poles in reinforced concrete - Asphalt slabs and Reclaimed asphalt pavement	- 50% concrete - 50% RAP	**ASFC**
Construction and Demolition waste	- "Mixed" building demolition rubble not differentiated: brick, concrete, plaster, sand, cement, ceramic, etc. - Ceramic Tiles (ceramic industry waste) - Industrial waste (steel / foundry slag, sandblasting dust)	- 50% demolition mix - 20% ceramic waste - 30% industrial waste	**CDW**
Stabilized Recycled concrete	- Concrete-based building demolition rubble: industrial floors, beams, pillars, concrete tiles, etc. - Reinforced concrete of vineyard poles	- 100% concrete rubble	**RCA**
Stabilized Crushed concrete sleepers	-Reinforced concrete of railway sleepers	- 100% concrete rubble	**STRV**
Mix of Crushed sleepers and foundry waste	- Reinforced concrete of railway sleepers - Industrial waste (steel / foundry slag, sandblasting dust)	- 60% concrete rubble - 40% industrial waste	**MTRV**

In the recycling plant any coarse extraneous material such as wood, steel, plastics and similar are mechanically removed. In the processing, any blocks larger than 50 cm in size is volumetrically reduced to smaller particles. Shredding, iron removing, screening is made via a large mill plant. The processing is applied to all the delivered materials, which are then piled into different aggregate batches, such as stocks of mixed rubble, ceramic and industrial waste.

After iron removing by magnet, part of material with the desired granulometry is obtained, such as 0/30 and 0/80, which can be mixed with the product obtained from the sieve connected to the large mill. The "oversized" material (greater than 0/30), will be shredded with the main mill. Finally, after grinding with the large mill, a part of the "oversize" material is discarded which undergoes manual sorting to separate unwanted materials (plastic, wood, paper, rubber, etc.) from the aggregate.

LABORATORY TESTS AND RESULTS ANALYSIS

The performed tests are based on the European standard EN13242, which is applicable to aggregates for unbound and hydraulically bound materials to be used in civil engineering work and road construction [36]. The physical and mechanical tests on the materials have been performed at the pavement engineering laboratory of the University of Bologna, while the leaching and chemical tests were completed at the CAWR department laboratories of the Coventry University in UK.

Granulometry

For all materials and mixes of aggregates commonly used in pavement layers, particles' geometry and their gradation have a dominant effect on the layer compactability and its load bearing properties. All the research recycled materials can be considered as well-graded aggregates (Figure 2), and their gradation falls inside the limit envelopes defined by common Italian specifications [37–39]. It should be noted that these gradations are susceptible to possible changes due to the compaction of the pavement layers. The target envelopes help into identifying materials that will be possibly dense and less susceptible to permanent deformations under traffic loads. Also, all the experimental gradation curves fall in the highlighted area, which corresponds to the overlapping of a number of common envelopes [40]. Despite their clear variability, all materials fall in the size range of 0 to 30 mm. An additional condition to be usually fulfilled by recycled aggregates is that the fraction passing through the 0.063 mm sieve should be less than two-thirds the fraction passing through the 0.250 mm sieve [41]. All the tested materials fulfilled this condition in their initial gradation.

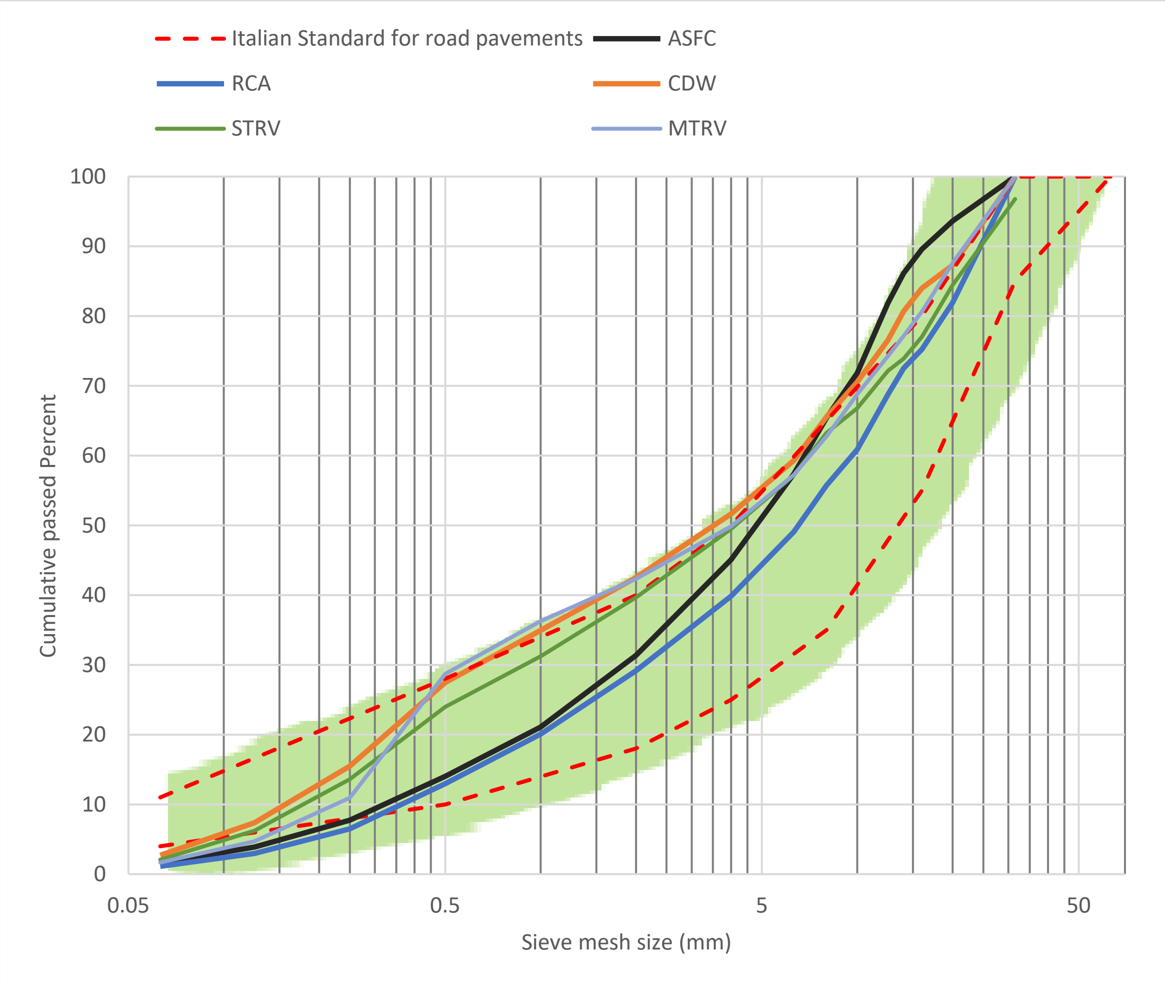

Figure 2. Aggregate size distributions of the recycled materials superimposed to common CDW aggregates envelopes [40].

Classification of constituents

The constituents of recycled granular materials highly depend on the sources of wastes and on the applied treatment processes and the conditions of the processing machinery. The EN933-11 standard provides some general categories for non-floating particles of recycled mixes such as cemented and concrete products (R_c), bituminous particles (R_a), natural and unbound aggregates (R_u), masonry elements (bricks and tiles, R_b), glass (R_g) and other materials (X) such as metals, wood, gypsum and cohesive materials [42]. The sorting results for the research materials are listed in Table 2.

Table 2. Results of Classification test for the constituents.

Constituent	Description	Recycled Concrete (RCA)	Construction and Demolition waste (CDW)	Crushed concrete and reclaimed asphalt mix (ASFC)	Crushed sleepers (STRV)
R_c	Concrete, concrete products, mortar, Concrete masonry units	63.58%	38.75%	27.21%	66.24%
R_u	Unbound aggregate, natural stone, Hydraulically bound aggregate	33.33%	27.38%	26.70%	31.72%
R_b	Clay masonry units (i.e. bricks and tiles), Calcium silicate masonry units, Aerated non-floating concrete	2.05%	30.42%	16.89%	0.42%
R_a	Bituminous materials	0.99%	3.27%	29.19%	0%
R_g	Glass	0%	0%	0%	0%
X	Other: Cohesive (i.e. clay and soil), Miscellaneous: metals (ferrous and nonferrous), non-floating wood, plastic and rubber, Gypsum plaster	0.02%	0%	0.01%	0.54%
FL (% in volume)	Volume of floating particles	0%	0%	0%	1.26%

In all materials, the natural unbound aggregates (R_u) do not exceed one third of the batch, but in recycled concrete and crushed sleepers, the quantities of concrete cemented aggregates are prevailing. As expected, masonry materials (R_b) and bituminous materials (R_a) are respectively abundant in CDW and ASFC.

As previously mentioned, during the laboratory compaction (with Proctor hammer), changes were expected in the gradations of the various constituents of mixes (Figure 3).

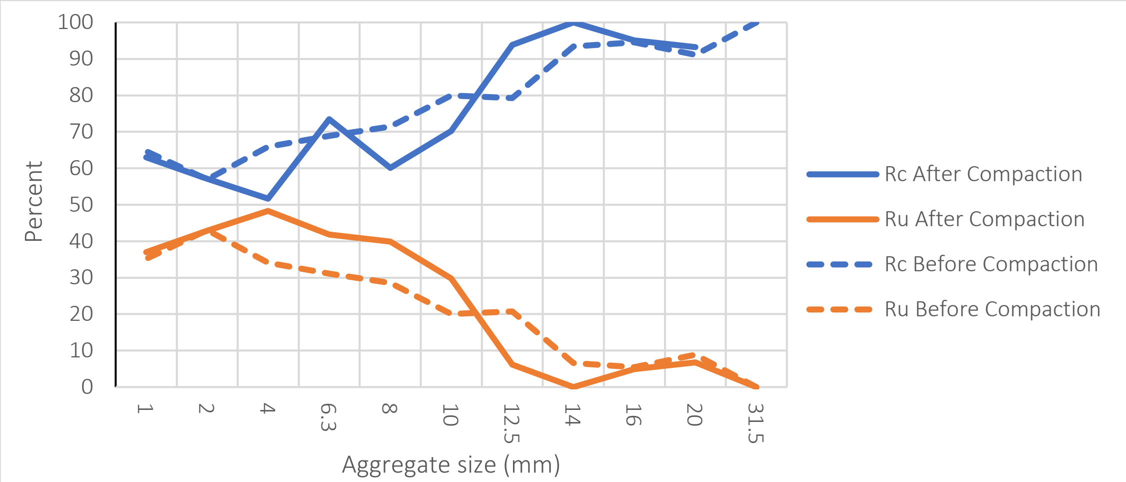

Figure 3. Change in the ratio of cementitious and natural aggregates in crushed concrete sleepers mix before and after compaction.

As shown in Figure 3, in both loose and compacted mixes of crushed sleepers concrete, unlike natural aggregates, the cementitious aggregates are more in the larger aggregate sizes. However, in the small sizes, the portion of natural aggregates are increased “after compaction”, if compared to the original loose batch. This shows that the compaction process produces some fine natural aggregates from larger cementitious clusters of aggregates, which are made of natural aggregates and attached mortar. This phenomenon is more clearly demonstrated in Figure 4, where the absolute percentage of cementitious constituent on each sieve is plotted. It is evident that in both materials, the Proctor compaction process changed the gradation of cemented aggregates, shifting them to lower sizes as they fragmented during the compaction. As a consequence, amount of fines increases while the quantity of coarse cemented material decrease with the separation of mortar and natural aggregates. The difference between compacted and loose materials distributions are similar for crushed concrete sleepers and mix of crushed concrete and reclaimed asphalt, and in both the largest decrease appears in the size range between 20 and 31.5 mm, transforming them to the 4-14mm size range. This confirms the possible changes in portions of constituents during compaction of recycled materials originated from civil engineering activities.

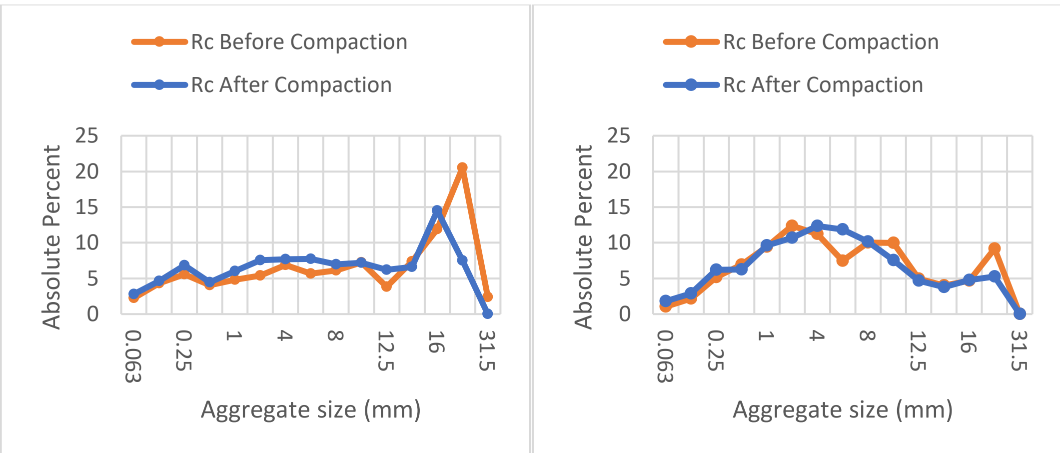

Figure 4. The absolute percentage of cementitious constituents before and after compaction. Left: Crushed concrete sleepers, Right: Stabilized mix of Crushed concrete and Reclaimed asphalt.

Resistance to fragmentation

The resistance to fragmentation of recycled materials is assessed using the EN 1097-2:2020 standard, commonly known as Los Angeles test. The standard procedure for the so-called Los Angeles Index requires the measurement of the mass passing 1.6 mm after 500 revolutions of the crushing drum. The results are shown in Table 5. In the dried method, the fines crushed in the drum were removed mechanically over the sieve, while in washed method (mentioned in standard) the removal of the fines passing from the sieve is done by water washing the aggregates over the sieve. The average values of the Los Angeles index for recycled materials are higher than those of natural aggregates, which is common and mostly because of weak mortars attached to the clusters of aggregates.

Table 5. Results of Los Angeles test (EN 1097-2:2020).

Material	Los Angeles Index (%)		
	Dried	Washed	Factory data
RCA (Recycled Concrete)	30	31	40
CDW (Construction and Demolition Waste)	36	37	40
ASFC (Mixture of Crushed concrete and reclaimed asphalt)	20	24	25

The washed indexes provide more reliable result than using the dry value because some fine material can remain in the latter despite the applied sieving. The mixture of crushed concrete and reclaimed asphalt undergoes the lowest fragmentation. CDW has a lower resistance to fragmentation than recycled concrete, which could be due to the higher amount of masonry constituents that have affected the resistance to fragmentation.

Proctor densification test

The laboratory compaction test is done by using a Proctor hammer and the corresponding modified procedure following the EN 13286-2 European standard [43]. The obtained moisture-dry density curves are shown in Figure 6. More pronounced bell-shaped curves are typical of materials that exhibit higher sensitivity to the change in moisture during compaction [44]. It appears that when the size distribution of aggregates tends to be well-graded, the moisture change has more influence on the variation in density. As expected the optimum moisture contents of recycled concrete and crushed sleepers are higher than those of other materials because of the higher water absorption due to possible residual reactions, which have been documented in crushed concrete aggregates in presence of moisture [45]. The Optimum Moisture Content (OMC) and Maximum Dry Density (MDD) of materials are shown in Table 6.

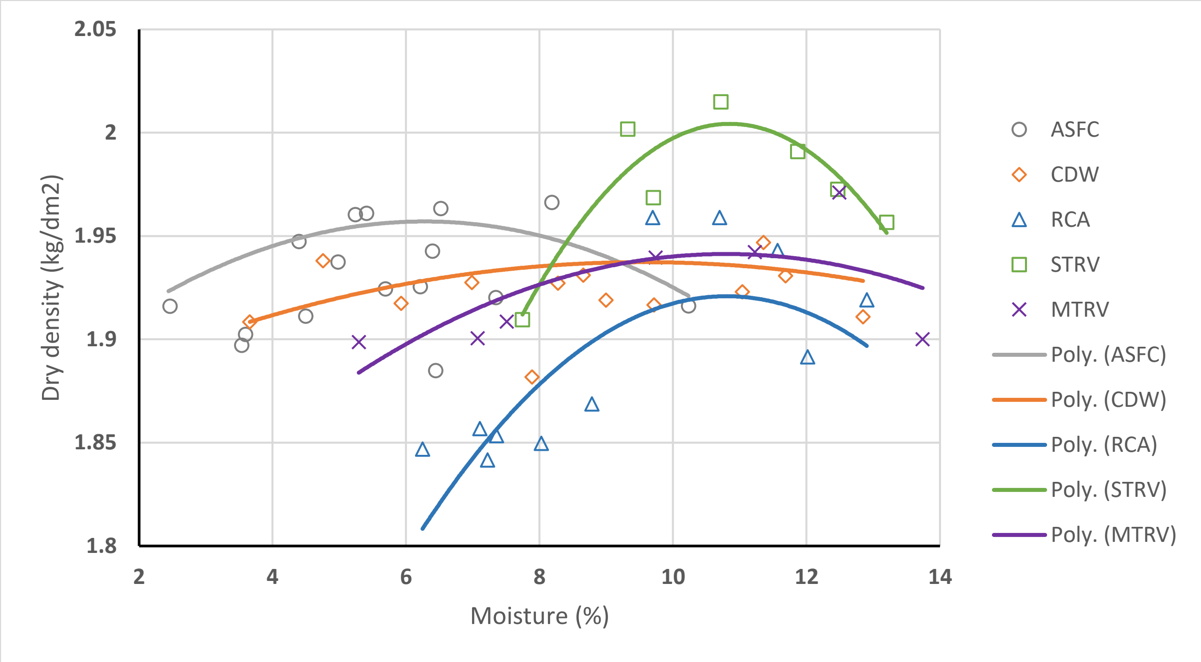

Figure 6. Moisture-Density curves from Proctor tests.

The differences found among the maximum dry densities and the optimum moisture contents was mainly caused by the difference in the density and the water absorption capacity of materials. The lowest OMC is for the mix of crushed concrete and reclaimed asphalt, more likely due to the hydrophobic behaviour of the bituminous constituents. In terms of density, the bituminous materials are clusters of particles and have lower density than concrete and natural aggregates, which often makes their maximum dry density (MDD) lower than recycled concrete or crushed sleepers concrete. Nevertheless, in this case the ASFC material only contains a 30% of RAP. The OMC for three concrete-based recycled materials are similar, however stabilized crushed sleepers has higher maximum dry density, which is also the highest among all recycled materials. This could be because of the type of cement used for manufacturing high-strength concrete sleepers, which can produce higher density concretes, if compared to standard Portland cement. Among the tested samples, all mixed recycled materials exhibit a flatter moisture-DD curve, more likely because of the well-graded distribution and the action of fines. Flatter moisture-DD curves for recycled materials, makes it also harder to measure the OMC and MDD comparing to natural soils, which usually have more pronounced bell-shaped curves. All the tested materials provided expected results in line with other similar materials. The crushed sleeper compacted mix is the heaviest.

Table 6. Optimum Moisture Content (OMC) and Maximum Dry Density (MDD) of recycled materials.

Material	OMC (%)	MDD (kg/dm^2)
ASFC	6.3	1.96
CDW	9.5	1.94
RCA	10.8	1.92
STRV	10.9	2.00
MTRV	10.8	1.94

California Bearing Ratio (CBR) test results

California Bearing Ratio test is used for evaluating in the laboratory the load bearing capacity of materials used for pavement deeper layers and follows a well-known penetration testing method for engineering materials. The CBR test can be performed in both un-soaked and soaked conditions in order to compare the materials stability and strength in various water content conditions. The recycled aggregates were compacted at their respective OMCs (Table 6) and subjected to the CBR test after soaking in tap water for 4 days. Based on the test results (Table 7), all the experimental recycled aggregates exhibit a high bearing capacity, which is consistent with previous results. Also, swelling after 4 days of soaking was a negligible, confirming the potential stability of the structural layer made with them.

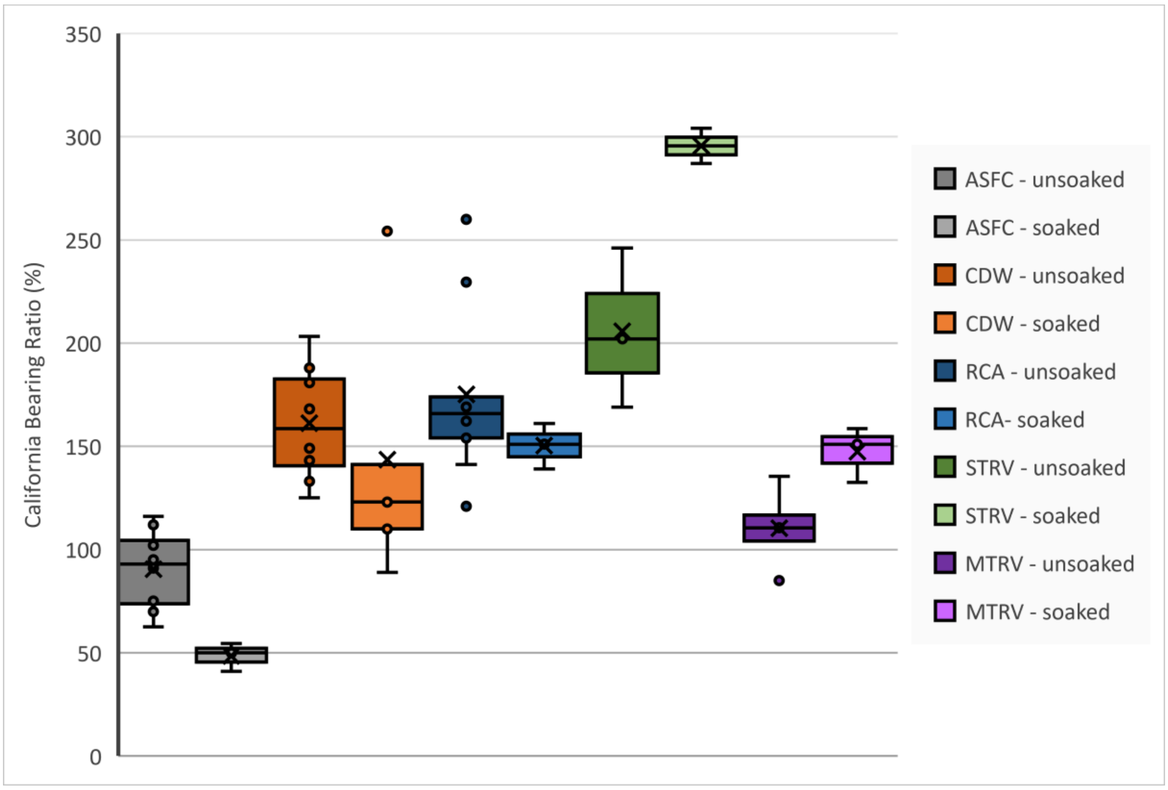

Figure 7. The CBR test results range for all recycled materials in un-soaked and soaked conditions.

In concrete category, for both STRV and MTRV, the soaked CBR values are higher than un-soaked ones, which can prove the existence of curing reactions when the cement in crushed concrete gets in contact with compaction water. These reactions have previously been proven by other researchers such as Kong et al. [45]. Similar to the compaction process data, the foundry waste in the MTRV could somehow affect the compacted structure of the sample, decreasing the CBR values if compared to the STRV. The lowest value of CBR belongs to ASFC, which could be caused by the lower mechanical properties of the clustered bituminous aggregates, which prevent the formation of a strong skeleton in un-soaked condition and may also limit the creation of cement bonds from the residual cement in the concrete constituents. CDW has higher CBR results in both un-soaked and soaked conditions comparing to ASFC, however it is lower than the other three concrete based materials. This could be related to the low mechanical strength of masonry and brick constituents of CDW recycled aggregates. Also, higher CBR values of STRV comparing to RCA could be as a result of the higher strength of cement mortar used for manufacturing concrete sleepers, which leads to a stiffer compacted structure.

Table 7. CBR test average results of all materials (%).

Material	un-soaked CBR *(% - average)*	soaked CBR *(% - average)*
ASFC	92	50
CDW	159	122
RCA	165	151
STRV	202	295
MTRV	110	150

Observing the effects of natural and concrete aggregates, as two main constituents of recycled materials contributing to the layer strength in un-soaked CBR (Figure 8), it is shown that the CBR of un-soaked samples of recycled aggregates does not clearly related to change in fraction of natural aggregate; However, percentage of concrete (in weight) has impression on the bearing capacity of the compacted recycled materials, by means of the linked changes in CBR. This could be generally related to their crushed rough surface and interlocking properties during compaction. The effect of the surface roughness of aggregates on mechanical properties of the compacted layers has been clearly demonstrated in previous studies like those of Bilodeau et al. and Hong et al. [46,47].

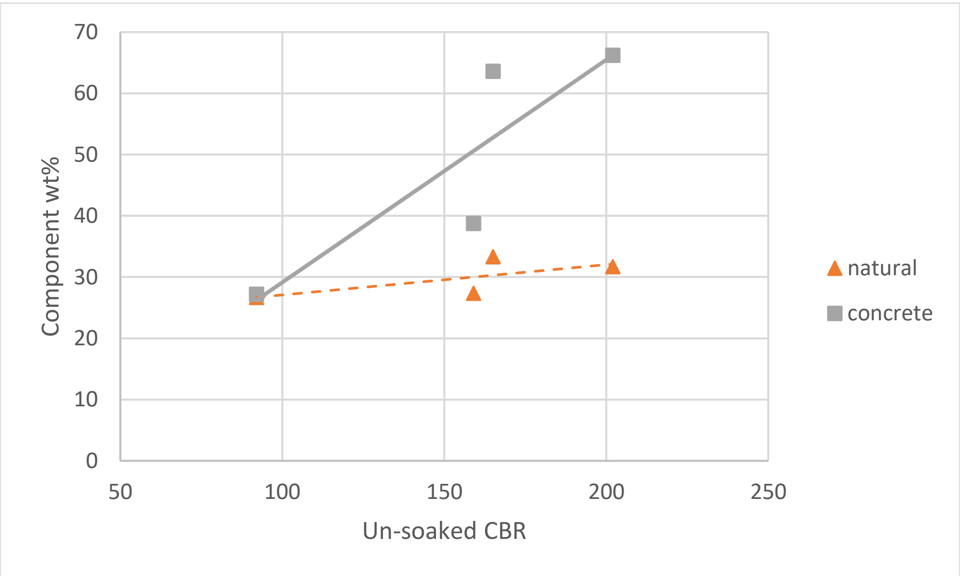

Figure 8. Correlation between un-soaked CBR values and percentage of main constituents of recycled materials.

Cemented mixes

The crushed sleepers mix and the mix of crushed concrete and reclaimed asphalt were used to extend the research to cement bound layers. In this section, the same materials have been evaluated as constituents of cement bound mixes for semi-rigid pavements. A range of cement binder percentages was adopted to optimize the mixture proportions. A set of three samples was prepared for each material and tested after 7 days of curing against compressive strength and indirect tensile strength, following the standards for cement-bound mixtures [48]. Results are listed in Table 8.

Table 8. Compressive and Indirect Tensile Strengths of two recycled cement-bounded mixes.

		Compressive Strength (MPa)		Indirect Tensile Strength (MPa)
	Cement Percent	Sample 1	Sample 2	
Mix of Crushed concrete and Reclaimed asphalt (ASFC)	2.5 %	2.74	2.99	0.21
	3.0 %	2.80	3.45	0.22
	3.5 %	3.29	3.16	0.23
Stabilized Crushed sleepers (STRV)	2.5 %	1.52	3.28	0.15
	3.0 %	2.87	3.46	0.23
	3.5 %	7.08	3.90	0.36

As expected, the quantity of cement binder plays a crucial role in the level of resistance achieved by the cured samples, both in terms of compressive and indirect tensile strength. Despite their variable gradation, the recycled materials reach satisfactory strength values and could be potentially employed in the construction of cement bound layers. The STRV mix appears to have a sharper increase in strength if compared to the mix made with ASFC and this behaviour is more likely to be attributed to the presence of bitumen coating the RAP particles. Durability shall be also assessed in future work.

Dynamic Surface Leaching Test

The leaching tests in the present study were carried out according to CEN/TS 16637-2 standard from European Commission Construction Products Regulation (EC-CPR). The horizontal dynamic surface leaching tests (DSLT) were carried out in triplicate on the 3 main materials as the STRV has very similar concrete composition to RCA. 176 g of ASFC, CDW and RCA materials were placed in glass tanks with sealed caps to prevent liquid evaporation. A liquid to solid (L/S) ratio of 10 was selected for the DSLT experiments. Deionized (DI) water with neutral pH was used as leachant in this study. and statistical analysis of the data from samples was performed using SPSS software (Version 21.0, SPSS, Chicago, Illinois). The DSLT experiments were carried out at a controlled room temperature of 20-25 °C. Samples were taken prior to the leachant renewal of the DSLT experiments after 0.25, 1, 2.25, 4, 9, 16, 36, and 64 days from the start of the assays. According to CEN/TS 16637-2 standard, the duration of steps before leachant renewal were 0.25, 0.75, 1.25, 1.75, 5, 7, 20 and 28 days. Three replicates of glass tanks containing leachants at same conditions as DSLT were prepared as controls. Electric Conductivity (EC) and pH of the samples from materials and controls of all-time intervals were measured using EC and pH meters. Samples were further investigated for the concentrations of heavy metals and trace elements including Al, As, B, Ba, Ca, Cd, Co, Cr, Cu, Fe, K, Mg, Mn, Mo, Na, Ni, Pb, Sb, Se, Si, Tl, V and Zn. The concentrations of the described elements for all time intervals, were measured using a Perkin-Elmer optima 5300 DV ICP-OES instrument. The cumulative concentrations of leached compounds were reported using the equation below (CEN/TS-16637-2 2014):

$$C_n = \sum_{i=0}^{n} C_i$$

where Cn (mg/m^2) is the cumulative concentration at the step (n) of DSLT test, Ci is the concentration of the element in the leachant at the step (n) (measured using ICP-OES analysis) and (i) is the time interval step.

According to the CEN/TS 16637-2 standard, the pH and EC of leachants from DSLT of ASFC, CDW and RCA materials were evaluated for samples from all time intervals. The results of the pH and EC evaluations are presented in Figure 5, respectively. The least change in pH during the DSLT experiments was associated with CDW with a range between 10.5 to 10.9. However, the pH value of leachant from RCA samples showed a larger variation (11.15-12.10). In general, the highest value of pH was observed from RCA samples (12.1). The excessive increase in pH of leachants in contact with RCA samples was due to the release of hydroxyl ions, leached from concrete materials in RCA [49,50].

The patterns of EC evolution in ASFC, CDW and RCA samples were similar to pH (Figure 5, b). This observation was due to the release of functional groups such as hydroxyl groups from cementitious material into the leachant medium, which resulted in the increase in EC of the solution [50,51]. In general, the EC of leachants from DSLT experiments increased from day 0.25 to 64 with the maximum occurring at day 64 for ASFC (1716 uS/cm), CDW (1284 uS/cm) and RCA (2358 uS/cm) materials.

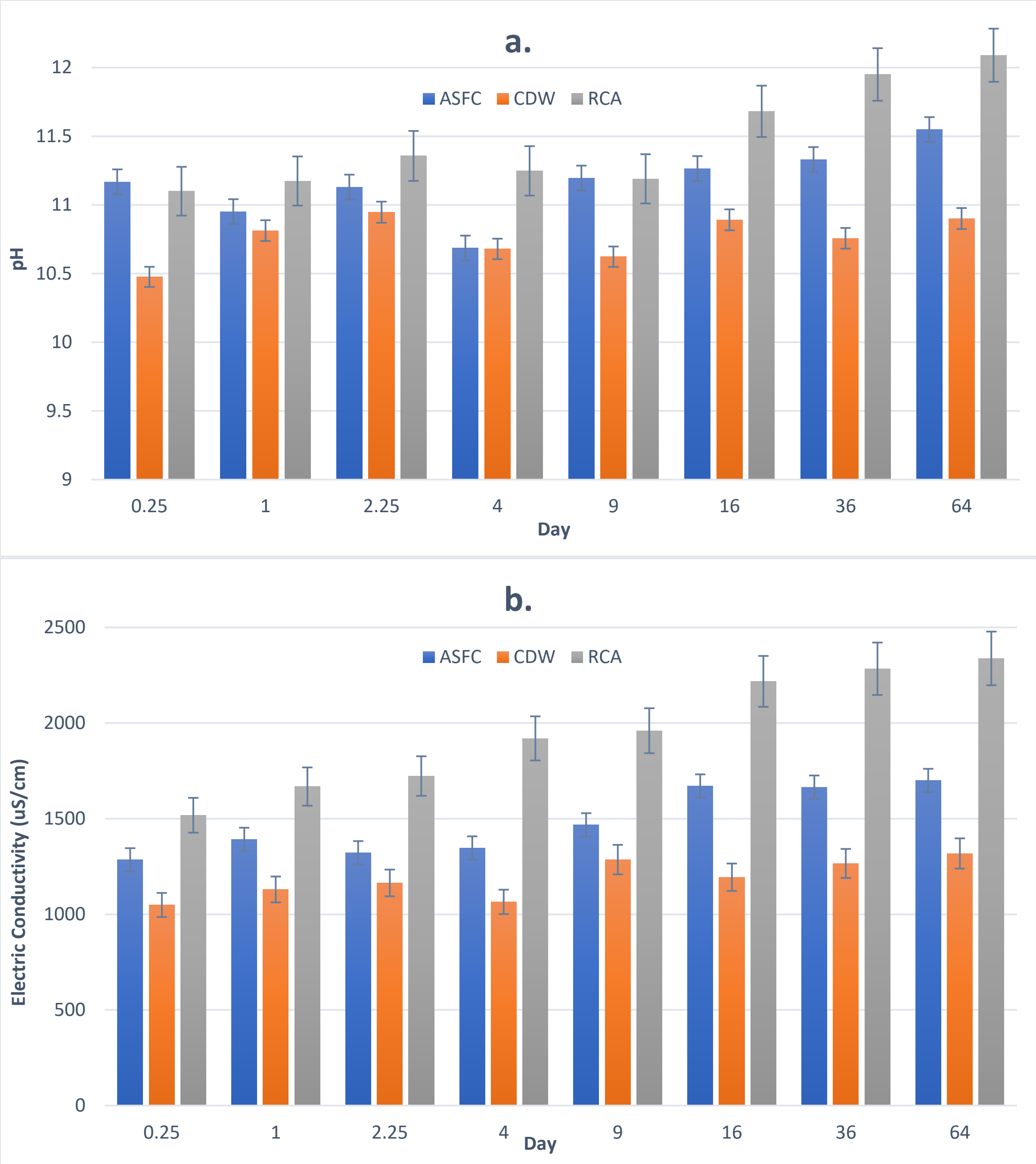

Figure 5. Development of (a) pH, and (b) EC values of the leachant in contact with ASFC, CDW and RCA materials during the DSLT.

The ICP-OES analytical assay was performed on control replicates and leachant samples from all the time intervals of DSLT experiments. The cumulative concentration of released heavy metals and trace elements per unit mass of ASFC, CDW and RCA materials are presented in Table 3. The concentration of all elements in control replicates were below the detection limit of ICP-OES instrument, which confirmed that the glass containers had no contribution in released substances from ASFC, CDW and RCA materials. According to the results, the highest concentration of released elements of Cd (0.0004 mg/L), Cr (0.0004 mg/L), Cu (0.0171 mg/L), Fe (4.7773 mg/L), Na (0.1731 mg/L), Ni (0.0157 mg/L), Pb (0.0303 mg/L), Sb (0.0005 mg/L), Tl (0.0053 mg/L), V (0.0461 mg/L) and Zn (0.0523 mg/L) were associated with ASFC samples. Concentration of elements including As, Cd, Sb and TL in leachants from RCA samples, were below the detection limit of the instrument. The highest concentrations of Al (8.7129 mg/L), As (0.0049 mg/L), B (0.0061 mg/L), Ba (0.0334 mg/L), K (0.4479 mg/L), Mg (0.0462 mg/L) and Si (0.0996 mg/L) in leachant were from CDW samples. No detectable concentrations of Cd, Mo and Sb were observed for CDW samples. These observations were consistent with previous studies on leaching behaviour of CDW [35,52,53]. The leached concentrations of the heavy metals and trace elements from ASFC, CDW and RCA materials shown in Table 3 were compared with limitations proposed in the EU Water Framework Directive (The Water Framework Directive 2000/60/EC). The released concentrations of all elements in leachants from DSLT experiments on ASFC, CDW and RCA materials, were far below EU Water Framework Directive thresholds. This observation revealed that the applications of ASFC, CDW and RCA under investigation in the present study, in the road construction can be considered safe.

Table 3. Cumulative concentration of released heavy metals and trace elements from ASFC, CDW and RCA materials during DSLT (mg/L).

Element	ASFC	CDW	RCA
Al	4.3365	8.7129	4.8215
As	0.0031	0.0049	BDL*
B	0.0014	0.0061	0.0015
Ba	0.0062	0.0334	0.0147
Ca	1.7884	1.9141	28.3331
Cd	0.0004	BDL	BDL
Co	0.0007	0.0009	0.0013
Cr	0.0205	0.0107	0.0045
Cu	0.0171	0.0015	0.0057
Fe	4.7773	0.0404	0.9241
K	0.1610	0.4479	0.1896
Mg	0.0222	0.0462	0.0398
Mn	0.1064	0.1498	0.6065
Mo	0.0003	BDL	0.0009
Na	0.1731	0.0811	0.1915
Ni	0.0157	0.0131	0.0065
Pb	0.0303	0.0275	0.0074
Sb	0.0005	BDL	BDL
Se	0.0009	0.0036	0.0088
Si	0.0764	0.0996	0.0437
Tl	0.0053	0.0020	BDL
V	0.0461	0.0139	0.0063
Zn	0.0523	0.0255	0.0306

*BDL: Below Detection Limit

Chemical composition of Recycled Mixtures

Ground samples of ASFC, CDW and RCA aggregates were dried in oven at 105°C. 0.5 g of dried samples were digested with 10 mL of analytical grade nitric acid (provided by Fisher Scientific UK Ltd) in closed polytetrafluoroethylene vessels in a microwave oven. The microwave oven operation conditions were as follows:

Step 1: 5 minutes of heating time, 17-20 atm of pressure and 60% of power.

Step 2: 10 minutes of heating time, 20-26 atm of pressure and 80% of power.

Step 3: 10 minutes of heating time, 26-30 atm of pressure and 100% of power.

The total content of elements including Al, As, B, Ba, Ca, Cd, Co, Cr, Cu, Fe, K, Mg, Mn, Mo, Na, Ni, Pb, Sb, Se, Si, Tl, V and Zn were evaluated for acid digested samples of ASFC, CDW and RCA using the ICP-OES analytical technique.

The total content of heavy metals and trace elements were evaluated for ASFC, CDW and RCA materials using a microwave assisted acid digestion method. Table 4 shows the mean content of elements in aggregates under investigation. According to the results, RCA aggregates comprised of the highest content of Ca (26284 mg/kg), Co (10.12 mg/kg), Cr (42.62 mg/kg), K (1275.87 mg/kg), Mn (954.71 mg/kg), Mo (6.12 mg/kg) and Na (1152.69 mg/kg). The observed chemical composition of the RCA was in the range reported by previous studies [54]. CDW had the highest mean content of Al (20104 mg/kg), Cu (41.83 mg/kg), Fe (26944 mg/kg), Si (1095.5 mg/kg), Ni (94.12 mg/kg), Tl (12.65 mg/kg) and Zn (280.84 mg/kg). Diotti, have reported Al, Fe and Si as the most abundant elements in CDWs [55]. The high concentration of these metals may be due to existence of industrial wastes including steel, foundry slag and sandblasting dust in the CDW. The analytical evaluation of the acid digested samples revealed that ASFC had the highest content of As (29.63 mg/kg), B (14.76 mg/kg), Ba (126.88 mg/kg), Cd (4.56 mg/kg), Mg (267.75 mg/kg), Pb (146.68 mg/kg), Sb (11.6 mg/kg), Se (18.52 mg/kg) and V (58.44 mg/kg). The observed chemical composition was in the range reported by previous studies on ASFC [56,57].

Table 4. Chemical composition of ASFC, CDW and RCA materials (mg/kg).

Element	ASFC	CDW	RCA
Al	9265	20104	17427
As	29.63	12.63	5.12
B	14.76	8.27	10.76
Ba	126.88	13.84	90.25
Ca	97889	111467	145284
Cd	4.56	2.14	1.83
Co	8.28	3.41	10.12
Cr	28.77	22.17	42.63
Cu	13.14	41.83	27.14
Fe	3021.56	26944	7259.34
K	1045.46	945.23	1275.87
Mg	267.75	111.57	198.22
Mn	856.63	582.22	954.71
Mo	4.59	1.15	6.12
Na	647.27	561.23	1152.69
Ni	55.27	94.12	42.89
Pb	146.68	94.73	55.87
Sb	11.6	4.25	4.53
Se	18.52	8.67	15.51
Si	396.17	1095.5	410.23
Tl	8.48	12.65	1.89
V	58.44	35.64	42.87
Zn	49.61	280.84	141.33

CONCLUSIONS

The present study investigates the laboratory behaviour of different recycled aggregates obtained from civil engineering activities and to be used as construction materials for the deeper layers of pavements. The research focused on common recycled aggregates and it also included some uncommon materials such as crushed concrete from railway sleepers and foundry sands. Apart from the traditional geometrical, physical and mechanical assessments, the experimental mixes have undergone a specific laboratory analysis on their chemical composition and leachants, in view of their possible use in pavements layers where the contact with percolating and vadose zone waters may happen and generate contamination. In the light of the obtained results the following conclusions can be drawn:

It is confirmed that the fragmentation of recycled materials under compaction can obviously change the gradation of mixes, thus affecting the compacted layer properties in terms of density and load-bearing capacity.

The type of crushed concrete has a clear influence on the load bearing properties of mixes. High strength concrete aggregates records higher CBR result because of a more effective mechanical interaction between the aggregates and stronger contact points within the compacted skeleton.

Soaking in water compacted samples of recycled mixes can have opposite effects in terms of load-bearing capacity. In case of crushed sleepers, the soaked values are higher than un-soaked ones.

The higher dependency of un-soaked CBR value of mixes on the amount of concrete constituents compared to natural aggregates, shows that the presence of concrete aggregates plays a more important role than the that of natural aggregates in the recycled mixes.

The use of reclaimed asphalt in unbound mixes can have some disadvantages other than that of using a bituminous material as a black rock: load-bearing capacity and strengths in the cement bound conditions are reduced if compared to non-bituminous mixes.

During the assessment of recycled aggregates in cement bound mixes materials mainly containing crushed concrete showed better performance than batches with concrete and bituminous materials. This can be attributed to the presence of bitumen that limits the potential cementitious bonds between the aggregates.

The results of the chemical composition evaluation of ASFC, CDW and RCA showed that the CDW had the highest content of metals Al, Cu, Fe, Si, Ni, Tl and Zn. Moreover, the lowest release of trace elements during the DSLT experiments was associated with RCA.

Overall, the release of heavy metals and trace elements from ASFC, CDW and RCA materials were far below the EU Water Framework Directive.

Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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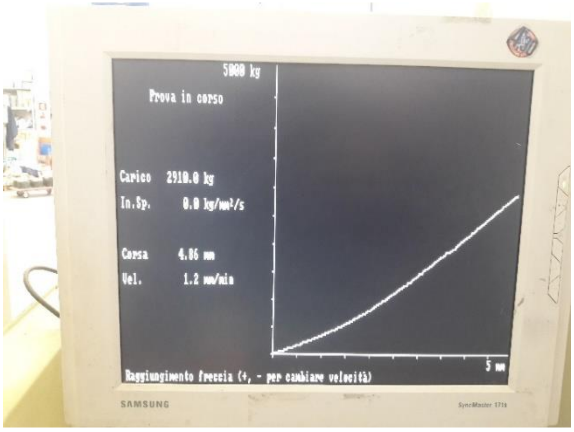
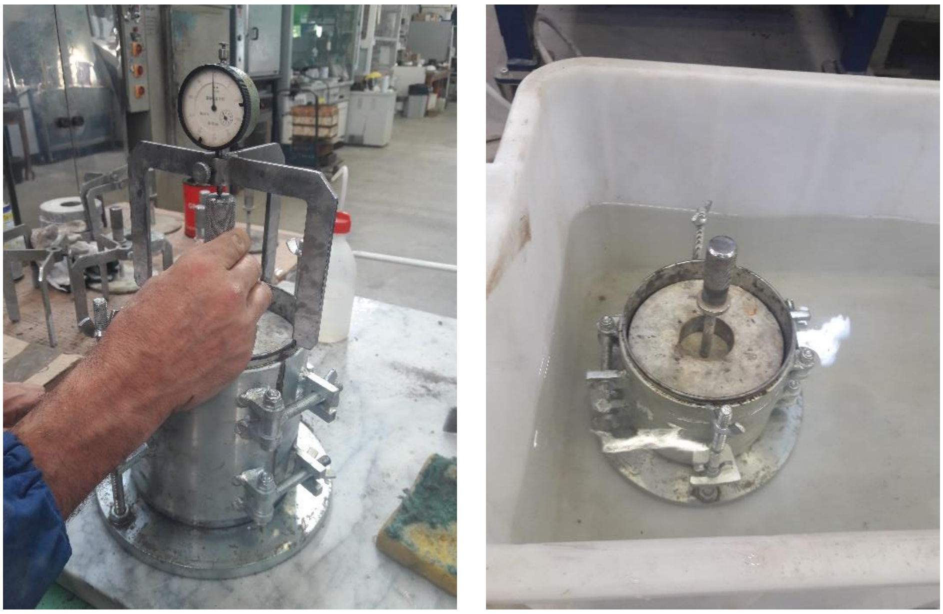
APPENDIX: ADDITIONAL PICTURES RELATED TO CHAPTER 3

Sampling from aggregate batch for laboratory tests.



Left: Merceology test and constituent classification for 20mm sieve. Right: Load-Displacement graph of The CBR test

Left: The surface of mould bottom face sample compacted by proctor for CBR test. Right: The track of CBR penetrating piston after the test.



Left: Installing and setting of length gauge for soaked CBR samples. Right: Merging the CBR mould in tap water with weight ring.

The merged proctor compacted samples.

The Los Angeles test drum.

CHAPTER 4: CASE STUDY: CONSTRUCTION OF AN IN-SITU LAYERED EXPERIMENTAL PAVEMENT WITH RECYCLED MATERIALS AND INTELLIGENT COMPACTION QUALITY CONTROL METHODS

FOREWORD

The goal of this chapter, is to evaluate the performance of the selected mixtures of recycled aggregates in real construction and traffic conditions. An in-situ trial site is designed and entirely built with recycled aggregates in a simple two layered pavement made of an un-bound sub-base and a cement-bound base layer. The content of this chapter is presented in two parts. In the first one, the data obtained from intelligent compaction rollers of unbound and cement-bound layers were analysed, and the trend changes in vibrational bearing capacity plot were evaluated as an indicator of layer stiffness. In the second part, the correlation of common deflectometric and volumetric spot test results with the roller compactor recorded data is studied in order to propose simple criteria for construction quality control purposes and simple operation guidelines for rural low traffic road pavement layers.

The durability of the pavement, especially those where the unbound layers are directly exposed to weathering actions, has direct relation with the effectiveness and persistence of compaction in the various layers of pavements. The vibratory modulus of Continuous Compaction Control rollers can be used as an excellent and effective indicator of the layer stiffness and the achieved densification. Indeed, minimizing the passes of roller compaction decreases the cost and time needed to meet the specifications. The aim of this chapter is to study the performance of the selected recycled materials, evaluate the development of stiffness and the effectiveness of compaction operation on both layers. In parallel, the response and behaviour of different blends of recycled aggregates and their compaction evolution is analysed, based on literature data, obtained laboratory results and correlations of different spot tests with the recorded bearing capacity.

The work presented in this chapter is described in two published conference papers as listed below:

1- **S. Pourkhorshidi,** C. Sangiorgi, D. Torreggiani, P. Tassinari, Assessment of construction and demolition waste materials for sublayers of low traffic rural roads, in: 11th International Conference on the Bearing Capacity of Roads, Railways and Airfields, Vol. 3, CRC Press, London, 2022: pp. 480–490. https://doi.org/10.1201/9781003222910-50.

Authorship declaration

A summary of each author's contribution to this work is provided below.

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Writing – original draft preparation:	S. Pourkhorshidi
Writing – review and editing:	C. Sangiorgi
Writing – final editing:	S. Pourkhorshidi, C. Sangiorgi
Supervision:	P. Tassinari, D. Torreggiani

2- **Pourkhorshidi, S**., Sangiorgi, C., Torreggiani, D., Tassinari, P. (2023). Integration of Spot Tests and Vibratory Roller Data in Rural Road Pavement Layers Made with Recycled Aggregates. In: Gomes Correia, et.al. (eds) Trends on Construction in the Digital Era. ISIC 2022. Lecture Notes in Civil Engineering, vol 306. Springer, Cham. https://doi.org/10.1007/978-3-031-20241-4_20

Authorship declaration

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Eleventh International Conference on the Bearing Capacity of Roads, Railways and Airfields, Volume 3 – Hoff, Mork & Saba (eds)

Assessment of construction and demolition waste materials for sublayers of low traffic rural roads

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ABSTRACT: The need for exploiting massive amounts of natural raw materials for constructing pavements of roads as a key element for development of infrastructures in modern age, together with enormous production amounts of wastes related to civil engineering activities as biggest portion of solid waste generated all over the world, have highlighted the importance of utilizing recycled aggregates of these materials in road pavement layers. The key factor in this quest, is to evaluate load-bearing abilities of various kinds of waste aggregates. Aggregates of reclaimed asphalt, pre-stressed or normal concrete, masonry and demolition waste (CDW) exhibit different behavior under loading after compaction. The ideal situation would be to achieve the densest compacted and durable layer in order to get the highest durability, comparing to traditional road materials. In this study, aggregates from four types of recycled materials are being subjected to study for unbound and cemented pavement layers. Initial laboratory evaluations of size and composition are followed by constructing a field on a subgrade with high non-homogenous surface. Vibrating elastic modulus (E_{vib}) for these materials were determined by Continuous Compaction Control (CCC) Oscillating Rollers. It is observed that, despite the weaknesses arisen from weak components such as masonry and elongated tiles, the stabilized distribution of the particle size can accelerate reaching to final compaction of unbound aggregates with roller passing. This process could be repeated with more or less same pattern in cemented layer, which exhibited an enhanced stiffness and uniformity in order to minimize the weak parts of non-uniform subgrade layer, and provide a high rigid pavement.

Keywords: construction and demolition waste, recycling, continuous compaction control, foundation layers, cemented layers

1 INTRODUCTION

By developing new innovative technologies for road construction in recent years, rollers with continuous compaction control (CCC) capability are more and more utilized for constructing the various layers of pavements. Achieving high efficiency of compaction by these rollers has been a key topic for many researches. Most roller manufacturers follow the corresponding line of evaluating how the soil under compaction reacts to the roller and use this measurement to determine parameters referable to bearing capacity (Dondi et al. 2014).

DOI: 10.1201/9781003222910-50

On the other hand, the need for providing raw materials for pavements is soared in recent decades due to huge amount of road construction all over the world, especially in developing countries, owing to facilitated technological possibilities and solutions. Considering large values of waste materials obtained from civil engineering activities, environmental, sustainability and economic considerations strongly suggest applying recycled construction and demolition waste materials as a substitute of virgin raw materials (Pourkhorshidi et al. 2020, Kovanda 2020, Tansel 2020).

The importance of rural roads in stimulating both economic growth and social development has been observed in many researches (Plessis-Fraissard 2007). The necessity for constructing rural road networks with the most cheap, durable and reliable possible methods with available materials, featured the study of unbound and cement-bound pavements to be used in the rural low-traffic pavements (Del Rey et al. 2016)

Researches on utilizing the recycled solid waste materials of construction and demolition in various layers of road pavements are vastly done all over the world (Barbudo et al. 2012, Gómez-Meijide & Pérez 2014, B. Gómez-Meijide et al. 2016); however, a limited number of them studied using continuous compaction control on recycled materials (Vennapusa et al. 2010). Sangiorgi et al. showed that construction and demolition material (CDW), laid using the same compaction process, could contribute differently to the bearing capacity of a double-layered embankment. Using CCC as an efficient method, they demonstrated that CCC measured E_{vib} moduli increase significantly as CDW compaction progresses. As the number of passes increases, the rate at which stiffness increases diminishes, and there is greater variability in stiffness for each kind of recycled material. Also, Light Weight Deflectometry (LWD) were found to correlate well despite different recorded value sizes for the moduli (Sangiorgi et al. 2015). In another study by Sangiorgi et al., it was concluded that CCC measured moduli shown significant increase with the progress of CDW compaction, even with values being highly affected by the presence of a layered structure and a weak subgrade. Also, the so-called Compaction Paths, starting from loose material values, show different trends of stiffnesses for different layers and materials. LWD measurements were very well correlated comparing to E_{vib} data. They proved that coupling CCC rollers and LWDs' measurements for the evaluation of earthworks should require a minimum CCC- measured value for given compaction amplitude (Sangiorgi et al. 2012).

In this research, an attempt is made to study the evaluation of stiffness by vibratory roller passes on four different recycled materials in unbound conditions, and also to see the stiffness gain in their cement-bound state.

2 MATERIALS

In total, five types of recycled materials obtained from civil engineering activities processed in an Italian high-quality recycling plant near the city of Imola offering licensed recycled aggregates for construction purposes, were utilized for constructing the unbound and cement-bound layers of a trial pavement. All the materials have European certificates and are in the range of 0-30mm size. Three out of five, have stabilized dense gradation envelopes, which make them suitable for being used in pavement applications. The amount of their floating elements is small. The compositions of these materials are listed in Table 1, and their particle size distributions are shown together with the size envelope of Italian authorities for road pavement materials in Figure 1. More technical properties of the materials are given in Table 2.

3 TRIAL FIELD AND COMPACTING METHOD

An experimental site was made in the mentioned recycling plant in Imola, Italy, in a location where high number of heavy trucks pass every working day (at least 5 to 10 heavy lorries each day). The subgrade of the site was constructed in the previous years with very thick

Table 1. Characteristics of the used recycled materials.

Material	Abbreviation	Containing	Composition
Stabilized mix of Crushed concrete and Reclaimed asphalt	ASFC	- Concrete-based building demolition rubble: industrial floors, beams, pillars, etc. - Vineyard poles in reinforced concrete - Asphalt slabs and Reclaimed asphalt pavement	- 50% concrete - 50% RAP
Construction and Demolition waste	CDW	- "Mixed" building demolition rubble not differentiated: brick, concrete, plaster, sand, cement, ceramic, etc. - Ceramic Tiles (ceramic industry waste) - Industrial waste (steel/foundry slag, sandblasting dust)	- 50% demolition mix - 20% ceramic waste - 30% industrial waste
Stabilized Recycled concrete	RCA	- Concrete-based building demolition rubble: industrial floors, beams, pillars, concrete tiles, etc. - Reinforced concrete of Vineyard poles	- 100% concrete rubble
Stabilized Crushed concrete sleepers	TRV	-Reinforced concrete of railway sleepers	- 100% concrete rubble from sleepers
Mix of Crushed sleepers and foundry waste	MTRV	- Reinforced concrete of railway sleepers - Industrial waste (steel/foundry slag, sandblasting dust)	- 60% concrete rubble from sleepers - 40% industrial waste

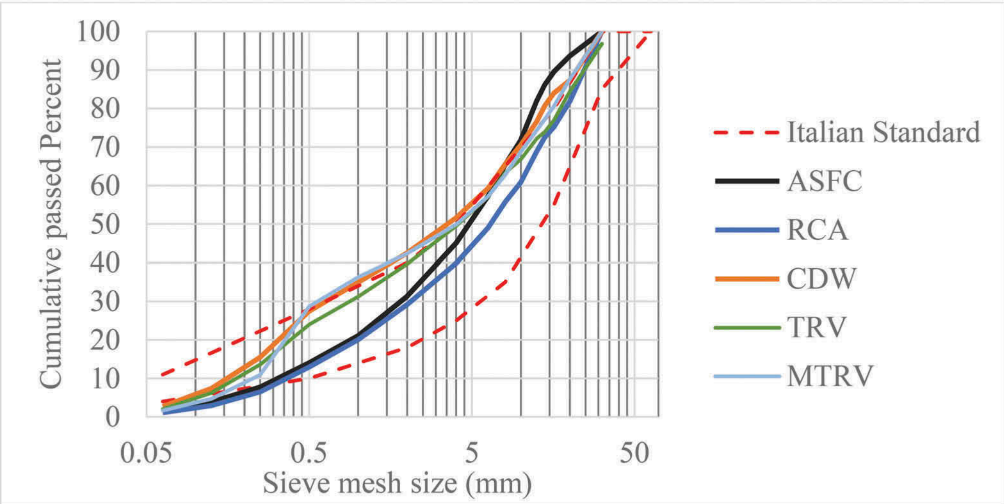

Figure 1. Particle size distribution of recycled materials.

layers of CDW and hardened by passing numerous vehicles including dozers and excavators. Four different layers were identified by means of a specific trench dug to the depth of 1.2 meters (Figure 2). Subgrade was placed in the past as a heterogeneous filling blend of CDW, clayey soil and other waste materials, compacted in several years by the plant traffic. The subgrade surface was roller-compacted and proven in 4 lanes before laying the first layer of new materials.

Table 2. Properties of recycled materials.

Material	Optimum moisture content (%)	MDD (kg/dm^3)	Un-soaked California bearing ratio (%)	Soaked California bearing ratio (%)	Los Angeles index (%)
ASFC	6.27	1.96	92	50	24
RCA	10.80	1.92	165	151	31
CDW	9.55	1.94	159	122	37
TRV	10.85	2.00	202	295	29
MTRV	10.79	1.94	110	150	30

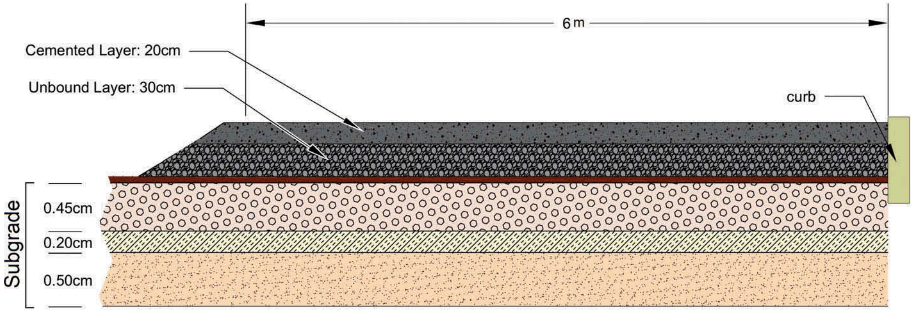

Figure 2. Schematic cross-section of subgrade, unbound and cement-bound layer.

An area 6 meters wide and 36 meters long was chosen for constructing the road and laying the selected recycled materials. The aerial image of the site is shown in Figure 3.

Figure 3. Schematic plan of constructed road and compaction lanes, Left: Sections of unbound materials and three lanes of roller compaction, Right: Cemented layers and lanes.

For target thickness of 30 cm considered for unbound base layer, about 35 cm depth of four type of materials was laid and leveled in the area each for each section length of 9 meters, after aggregates being hauled by loaders. After leveling by grader, the layer was compacted in three lanes by a heavy CCC roller setting a constant vibration amplitude. The subgrade and unbound base layer compaction and test processes were performed by means of a BOMAG

BW219 DH-5 compactor with a drum width of 212cm. Also, the speed and frequency of the roller compactor were controlled and fixed in order to maintain a comparable rolling condition for all three lanes. One each lane, 4 sets of forward vibrating and reverse static compaction were done and the stiffness data were collected.

For the Cement-bound layer, two materials of ASFC (mix of crushed concrete and reclaimed asphalt) and MTRV (mix of crushed sleepers and foundry waste) were selected to be mixed with cement and water, for a target layer of 20 cm thickness. 3% Portland cement was added to the two recycled materials of ASFC and MTRV with an automatic BLEND E050 blending machine, with the capacity of 14m^3 of cemented mix (10m^3 aggregate and 4 m^3 cement). The measured humidity of the mixes were 7.4% and 4.5% for ASFC and MTRV, respectively.

Two cemented materials were laid in parallel as shown in Figure 3, each layer had a width of 3 meters in order to create 8 different layered pavements in the trial site. One lane of vibrating compaction per each cement-bounded material was done by a BOMAG BW174AP-4V AM roller in order to compact and simultaneously evaluate the vibratory stiffness. A Lightweight deflectometry (LWD) was done in between the passes over the cemented material by mean of a ZORN ZFG2000 portable deflectometer.

The specifications of compacting rollers are reported in Table 3.

Table 3. Specifications of roller compactors.

	Subgrade and Unbound Base layer	Cement-bound layer
Model	BOMAG BW219 DH-5	BOMAG BW174AP-4 VAM
Mass	19400 kg	9500 kg
Drum width	212 cm	170 cm
Linear load	60.1 kg/cm	29.8 kg/cm
Roller speed (average)	3.7 km/h	2.4 km/h
Vibration frequency	24 Hz	45 Hz
Manual Amplitude	1.2 mm	0.8 mm

4 RESULTS AND DISCUSSION

The output of the rollers included E_{vib} graphs plot versus the longitudinal position of the roller compactor. The triggering of the data acquisition system was done manually at each forward pass. Data were saved in the cloud and printed on paper for further analysis. Matching of start-end points was made by means of reference points.

4.1 *Stiffness variation*

The E_{vib} values of the subgrade lanes are shown in Figure 4. The dashed lines show the adjacent sections of the subsequent unbound layer which would be layered in next stage. It is shown that despite revealing an inhomogeneity, stiffness modulus of all lanes follow similar patterns all over the length of the field. At a distance of 14 meters, there was a pipe passing under the subgrade which caused the weakness clearly visible by decrease in the E_{vib} values. The first lane had a lower E_{vib} graph which could be due to proximity to the concrete curb, from which trucks are usually distant for maneuvering. The overall width of subgrade is less than four lanes done with roller drum width of 212 cm, so the drum accelerometer sensor of roller which is located in one side of the drum, had fallen over previously roller-proven lane. Among the sections considered for the next layer of unbound materials, it is more or less obvious that section 2 has the lowest stiffness, while there is a peak in the border of sections 2 and 3.

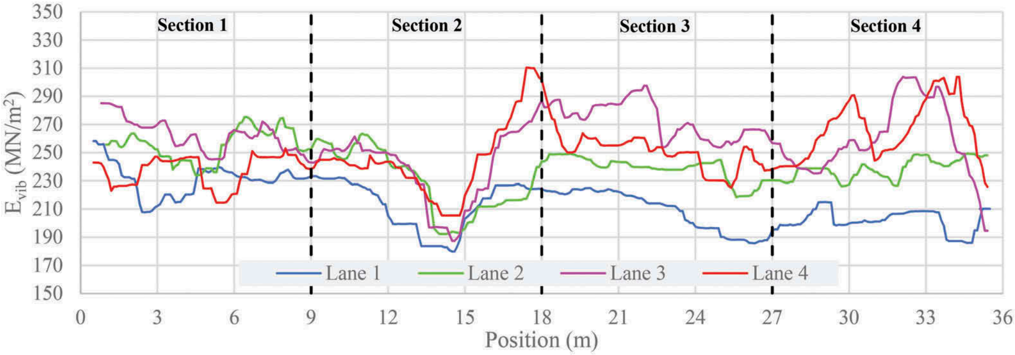

Figure 4. Vibratory modulus of subgrade (4 parallel overlapping lanes).

By constructing the new unbound base layer, another set of E_{vib} data was recorded for three new compaction lanes: east (close to curb), mid and west (the lane with free embankment). These data are shown in the graphs of Figure 5. There are some common details in all three graphs. First, all graphs follow the same pattern comparatively, considering subgrade stiffness inhomogeneity and diversity in materials of sections. For example, the location of weak stiffness regarding to weakness of subgrade under the pipe is obvious in all graphs, in spite of becoming less distinct in the west lane which is far from the curb. Secondly, the value of overall E_{vib} increase by the number of rollers passes. The E_{vib} increasing in various sections are noticeably different. In CDW, the E_{vib} graphs are closer to each other pass 1 to 4, but for other materials, especially RCA, the increase in E_{vib} is clearly visible. This could be related to many factors including the composition of mix constituents and their resistance to fragmentation. For materials with larger quantities of cementitious particles, the resistance to breaking under compaction is higher than CDW which has mainly masonry and bricks particles.

Yellow dashed lines shown the average E_{vib} value of the last pass in each section of material. It is seen that the order of E_{vib} value in the three section of CDW, RCA and ASFC is more or less the same for all lanes: CDW has the lowest value and ASFC has the relatively high average E_{vib} value. The section of TRV show a different behavior in east and west lanes which could be due to the free end edges of the embankment and the effect of subgrade stiffness variations. The relative values of final pass vibration stiffness of each section are not completely in agreement with the materials properties of each sections, which for some CDWs are relatively low (Poon & Chan 2006).

In the east lane, the drastic variations of E_{vib} are seen in first pass, which change to smoother peaks in the last pass (pass 4). However, despite a similar trend is repeated in E_{vib} of west lane, but some new peaks appear by increasing the number of passes. This proves the fact that, at least two different mechanisms contribute to the recorded E_{vib} value: first, the trace of varying stiffness of bottom layers (here: subgrade) on the upper layers, and secondly, the zonal high-compacted small segments created in last passes due to geometrical inhomogeneities in distribution of material layering and leveling.

The E_{vib} graphs of cemented layers are shown in Figure 6. As the material under compaction is unique all over the lane length, any change in the E_{vib} graph along the lane could be explained as the imprint of the base compacted layer on the superimposed cement-bounded layer.

However, the variation of E_{vib} plots in the cement-bound material over the length of the lane are much less than the variations in the unbound base layer, and cemented layers are more homogenous in terms of stiffness. The average value of E_{vib} for the last pass in all the sections (orange dashed lines) are more or less in the same range. This could be described as the positive outcome of well compacted base on the next layer, which provided a more uniform stiffness all over the lane. This homogeneity of stiffness is more evident in cemented MTRV than ASFC.

At the end of the base layer compaction, the mean E_{vib} values increase of approximately 20% with respect to pass 1 which was done over fresh material; it can be stated that each pass of vibratory compaction increased the E_{vib} of 5%, on average. In studying the CCC method, the achievement of maximum compaction is controlled through the percentage difference between the measured values (MVs) of two consecutive passes: compaction must be continued until the mean roller MV is less than 5% greater than the mean value from the previous pass. For small sites, this guarantees that no further compaction is possible and that if the weak spot tests are positive, than all the area has, on average, sufficient bearing capacity (Sangiorgi et al. 2012). Based on this, it is possible to infer that by only considering above mentioned 5% increment limit rule for the unbound layer, even one pass with the considered energy (frequency and amplitude) appears to be enough, which does not look to be cogent. So, in case of recycled materials, additional tests and methods will be necessary to support the sufficiency of vibratory roller passes for compacting the unbound layer. This is because their stiffness increments could be not fallen in a minimum range by escalating pass number, and persist in later passes.

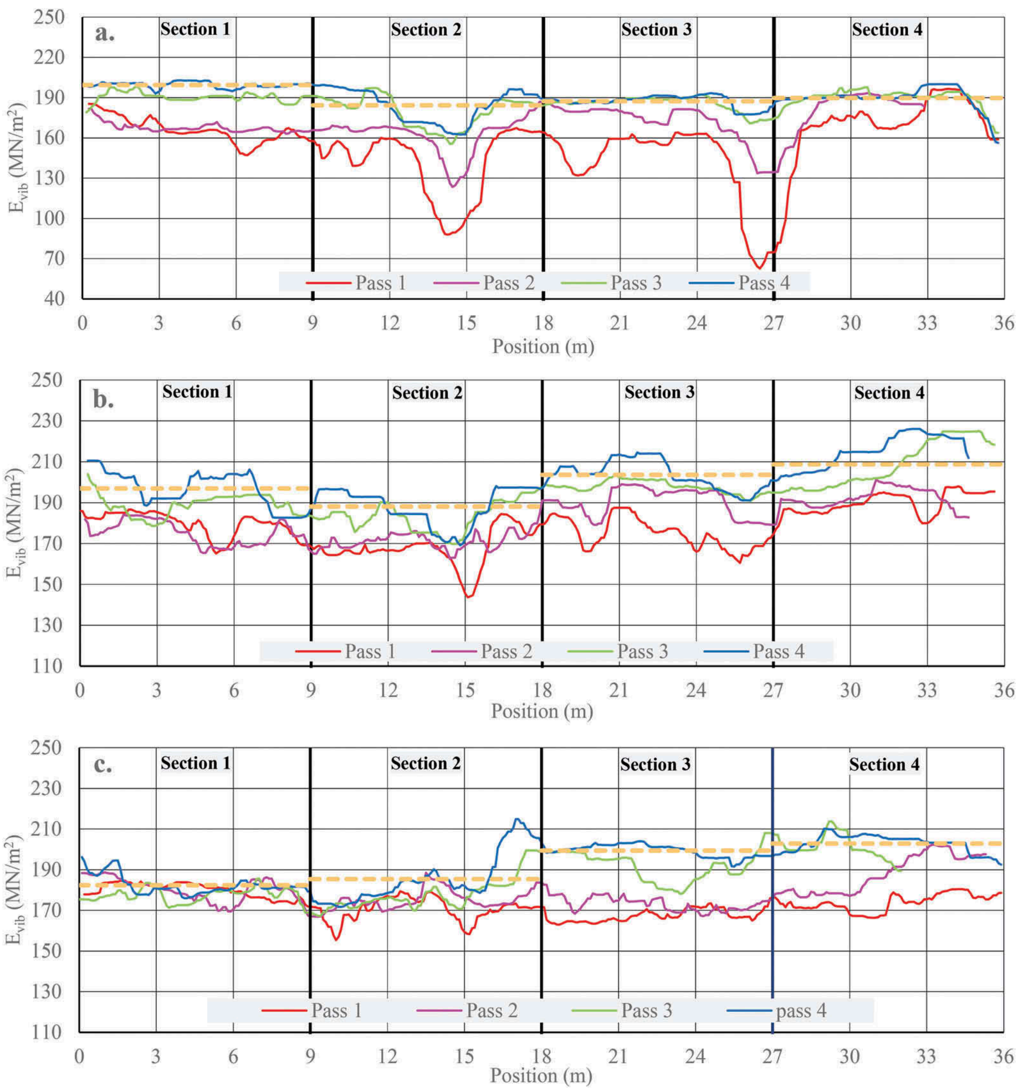

Figure 5. E_{vib} modulus of unbound base layer: a) East Lane, b) Middle Lane, c) West Lane, Section 1: ASFC, Section 2: RCA, Section 3: CDW and Section 4: TRV.

For cement-bound layer, alternatively, the distribution of E_{vib} graph increments is not uniform between passes. It is obvious that in cement-bound layers, the last passes have very close E_{vib} and graphs of final passes become more entangled. Considering that the total number of passes for cement-bound layer is 6, which is more than the passes of unbound layer (4 passes), it seems unlike unbound layer, there would be no increase in E_{vib} graphs of cement-bounded layer by any further extra passes of roller. This could be due to the fact that cement-bounded materials reach their final compaction limit in specified roller vibration energy (related to vibration frequency and amplitude) after third pass. The LWD evaluation between each pass (section 4.3) confirms this.

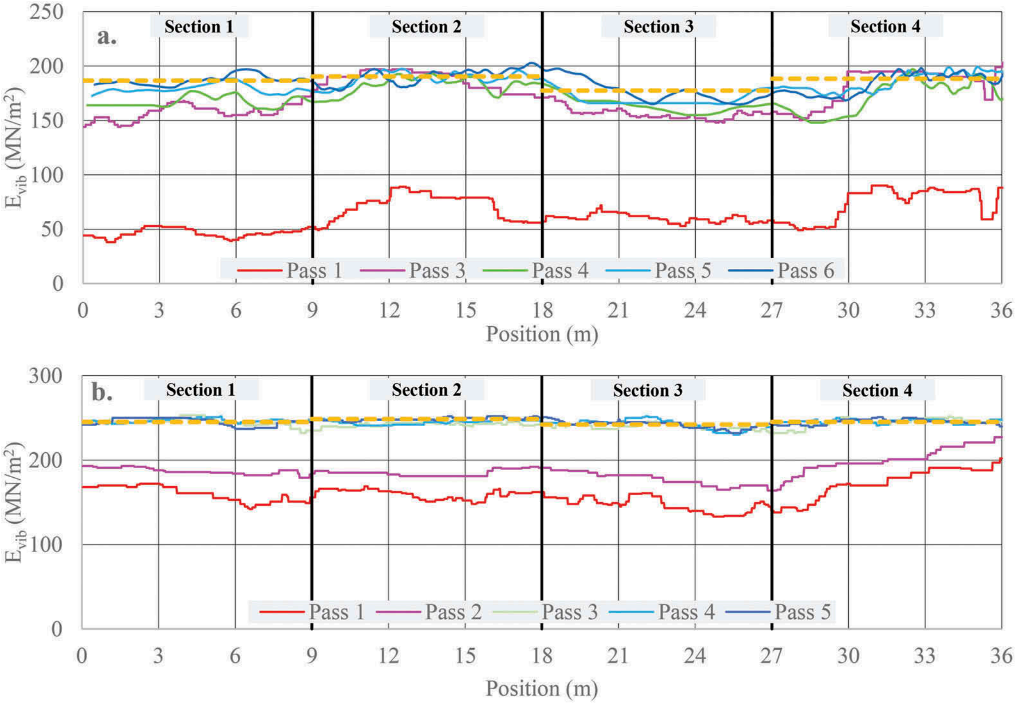

Figure 6. E_{vib} stiffness modulus in the cement-bound layer: a) Lane 1 - Cemented ASFC; b) Lane 2: Cemented MTRV.

4.2 *Analysis of compaction development*

The evolution of stiffness increase by the number of passes in unbound layer, can be represented in an E_{vib} pass "i" - E_{vib} pass "i+1" graph where the 45° line represents the values of equality between two subsequent vibratory passes, thus meaning that on the diagonal line no increase in stiffness has occurred. The clouds of points tend to get close to the 45° line as compaction progresses. Points below the line represent field positions where E_{vib} reduces from pass "i" to pass "i+1". This graph shown in Figure 7, where the overall progress can be traced by joining the mean values point of each couple of consecutive passes on the E_{vib} pass "i" - E_{vib} pass "i+1" plane.

This method represents no significant variation in the rate of change between the passes in unbound conditions, which could be in contrast with what could be visually seen in E_{vib} graphs of three roller compaction lanes for all sections. This dissimilarity proves the need for studying details of the stiffness gaining mechanisms in different recycled materials. The separation of different sections data clouds could prove how different materials exhibit different compaction patterns under the vibration of roller in various consecutive passes. An intuitive

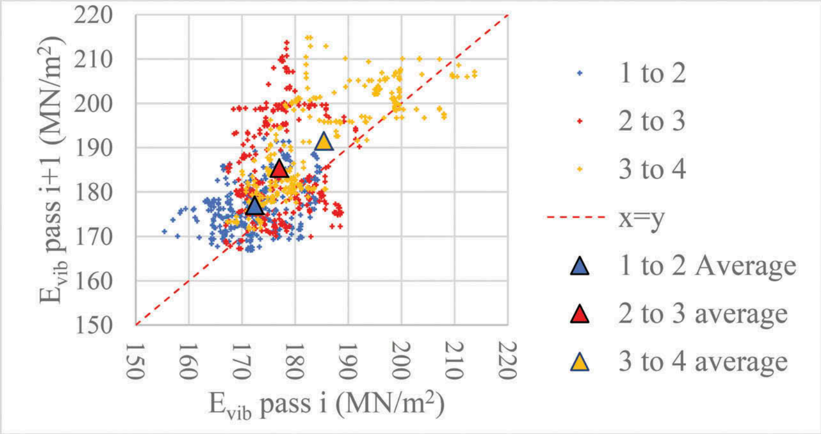

Figure 7. Stiffness values of unbound base layer in pairs of consecutive passes in all sections.

demonstration of the evolution of the stiffness could be given with the Compaction Paths (CP) polyline on each field, as shown in Figure 8.

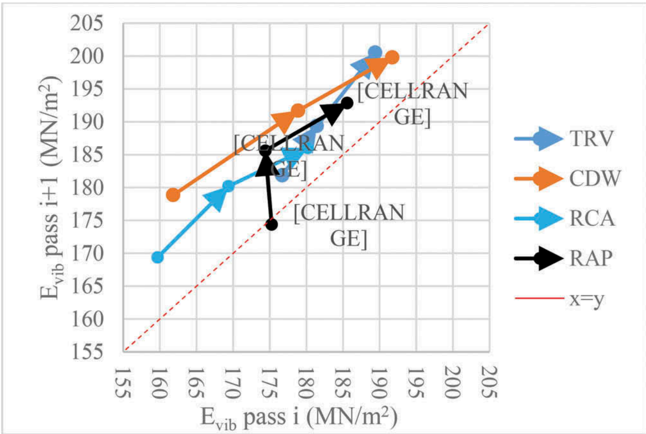

Figure 8. Compaction paths of different materials of unbound base layer.

As it is shown in Figure 8, the changing in stiffness of different materials by applying vibratory pass vary from one recycled material to the another. Considering Compaction path graphs, highest evolution in stiffness by roller compaction happens in CDW (with E_{vib} increase about 25%) and crushed sleepers (with E_{vib} increase of 15%)

The stiffness graphs in CDW became closer to each other in the last passes (3 to 4) than in initial passes (1 to 2). A possible explanation could be due to the type of substances and their portions, which are the only major dissimilarity among the different materials used in this study. CDW contains masonry and brittle tiles which fragmentation under compaction could change their particle size distribution and by increasing the number of passes, vibration could cause rearranging the broken fine particles as the compaction proceeds. This trend is also seen, but to a lower extent, in the RCA. However, in ASFC containing bituminous particles, the behavior is different, while the steps of E_{vib} increment increase in second to third pass and decrease in last ones (3 to 4), and for TRV containing high strength concrete aggregates the increment of stiffness increase pass after pass, making their stiffness development point higher the than 45° line. One possible explanation for extraordinary behavior of ASFC is presence of two processes working in opposite directions: Bituminous particles of ASFC are less brittle than other components (low Los Angeles test index of ASFC proves this) and they can also damp the energy of vibration due to their visco-elastic nature. This feature can cause the displacement of the aggregates under vibratory compaction in initial passes. This loosening effect can be compensated by the mechanism of filling voids between the aggregates by finer broken aggregates (of other brittle components, such as cemented particles). This improves the compaction degree, diminish the stiffness increment in the last passes and makes the compaction path converge to 45° line.

In crushed sleepers, due to the high strength of source pre-stressed concrete used for manufacturing the railway sleepers, the energy of vibrating compaction roller could not be enough for smashing all coarse aggregates and only minor change in size distribution would happen. This can be followed by eased particle displacement and the process continues in next passes as most coarse aggregates remain, which causes the material gain stiffness by each pass.

4.3 *Light weight deflectometry*

The evolution of the stiffness of cement-bound layer by the passes measured by LWD point test is shown in Figure 9. It is evident that there is an optimum number of passes for cement-bound layers in order to reach their highest stiffness by vibratory roller compaction. This graph is in agreement with the E_{vib} graphs, where the last passes of the cement-bound layer are very close to each other, and they do not show any extra increment in stiffness by further passes. It is seen that ASFC achieves stiffness by less passes than MTRV in cement-bound layers. Moreover, the rate of reaching the final stiffness from first pass in ASFC is almost twice the one for mixed crushed sleepers. These observations could be an indication of the fact that the compaction energy needed for reaching an optimal compaction in recycled materials with hard high-strength components are higher than those with weaker aggregates.

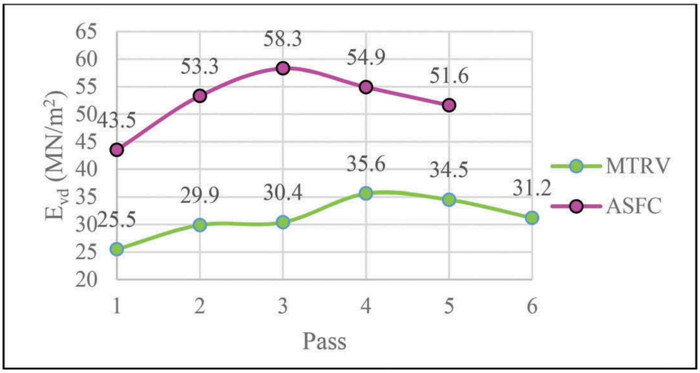

Figure 9. Lightweight Deflectometry test (LWD) results after each roller pass over cement-bound layers.

5 CONCLUSIONS

In this research, five types of recycled aggregates from waste of civil engineering activities were utilized for constructing unbound and cement-bound layers for low traffic roads by using vibratory compaction roller and their embedded CCC systems. The following outcomes can be concluded:

- Different recycled materials exhibit similar behavior with different extent in vibrating roller compaction. Recycled materials with weak components -like masonry and brick aggregates in CDW- could gain stiffness in initial passes due to the fragmentation and change in aggregate size distribution, however, harder constituents like crushed high-strength concrete aggregates in crushed sleepers cause persisting the stiffness increase rate of the material until later passes of vibrating roller.

- Relying only on the CCC studies could not be sufficient for determining the number of necessary passes for all kinds of recycled material, as even first passes could appear to meet the rule of 5% increment. Therefore, supplementary tests and methods could be required to identify the number of vibratory roller passes for compacting the unbound layer.
- Compaction path shows the change in stiffness of different materials by applying consecutive vibratory passes. These paths vary from one recycled material to the other. CDW and ASFC show highest and lowest stiffness gains by consecutive passes, relatively. This could be due to different strength and brittleness of their constituents.
- Lightweight deflectometry test (LWD) suggests what was visible by E_{vib} records on cement-bound layers: there is an optimum number of passes for cement-bound material to gain stiffness during compaction. Extra passes will not increase the E_{vib} of the compacted material. This number could be different for various materials.

ACKNOWLEDGMENT

The authors acknowledge the Italian companies of C.A.R Inerti srl and BOMAG Italia srl for providing materials, technicians and necessary machinery for experimental field operations of this research.

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Integration of Spot Tests and Vibratory Roller Data in Rural Road Pavement Layers Made with Recycled Aggregates

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Abstract. Utilizing recycled aggregates of Construction and Demolition (C&D) and other wastes from different civil engineering activities in several layers of pavements, especially in low traffic roads, revealed a huge potential of improving sustainability in the infrastructures of rural transportation. Using modern smart technologies like Continuous Compaction Control (CCC) rollers for these materials needs performing studies to optimize the adopted engineering parameters and updating Q_C/Q_A assessment protocols. Spot tests such as in-situ densitometry, Plate Load Test (PLT), Light Weight Deflectometry (LWD) together with dynamic California Bearing Ratio (CBR), could contribute to the validation of the procedure of roller compaction. The correlation of these sets of data with the CCC results could present valid information on the stiffness development of different recycled materials from different sources and compositions, and their behavior under vibratory compaction. In this study, a number of spot tests were performed before and after constructing two superimposed layers of unbound and cement-bound recycled materials, compacted by CCC vibratory rollers, in order the evaluate the correlation of their results and the vibratory moduli. Despite the differences in the degree of correlation of spot tests and CCC data in sections of different recycled materials, similar trends were observed within the distribution of data from the field. The state of being unbound or cement-bound in trial pavements with recycled materials has effect on respond to vibratory roller and spot tests. Moreover, the correlation of various spot test results on different recycled materials expose the dissimilar responses related to their components, test contact area and test depth of effect on field pavement.

Keywords: construction and demolition waste, recycling, continuous compaction control, lightweight deflectometry, plate load test

1 Introduction

Rural and farm roads play a significant role in transport of farming goods, especially in countries with economies based on agriculture products and with nationwide distributed development model. Many researches have revealed the importance of rural roads in inspiring both economic growth and social development. Effective planning and implementation of sound rural road projects depend on a combination of suitable planning tools, an adaptable approach to engineering design, and reliable guidelines [1]. The considerable overall length of the rural road networks in many countries, together with the connected economic size of these infrastructure [2,3], reveals the importance of shifting towards more sustainable and durable design and construction solutions for these roads. Although asphalt and cement concrete pavements are widely used worldwide for their construction and in-service performances, their costs are high and they are usually seen having a lower compatibility with the rural environments. Considering that many rural and farm roads are still unpaved, often with a single unbound or cement-bound layer, the study of using more sustainable materials and valid construction solutions for these roads could enhance their serviceability, durability and construction efficiency, together with a number of environmental benefits [4,5]. Therefore, the authors considered necessary to conduct in-depth research on producing and constructing unbound and cement-bound layers for unpaved rural roads.

In the light of the above, the application of recycled solid wastes, in particular of aggregates, in pavements and infrastructures in general, is one of the recurring sustainable methods of reducing the use of ecologically harmful landfills [6,7]. This application calls for a vast range of studies on the properties of the waste materials, together with their behavior in real pavements and the determination of the optimum values of their parameters [8]. These materials are usually compared with virgin natural materials, which use in road pavements has been going on since the first applications of the pavement engineering approaches to roads [9,10].

With respect to novel construction solutions, in recent years, Continuous Compaction Control (CCC) has attracted attention as a modern method for improving roller compaction process efficiency of various layers of the pavements. Continuous compaction control systems are data acquisition devices installed on compaction equipment that continuously collect real-time information about the operation and performance of the compactor [11]. The successful implementation of CCC technology into the construction practice with recycled aggregates requires knowledge of the CCC measurement values and their relationships with the in-situ properties of the recycled materials that relate to their performance [12]. The outcome of the CCC devices is usually a set of vibratory modulus (E_{vib}) data that can be used to optimize the compaction process and for Q_C/Q_A purposes.

Along with CCC real time data, one of the most common methods to investigate the compaction efficiency and mechanical properties of the field compacted material is performing spot tests such as Light Weight Deflectometry (LWD) [13,14], Plate load test (PLT) and Dynamic California Bearing Ratio (dynamic CBR) tests. By the same load/settlement concept based on the Boussinesq theory, these tests evaluate the response of the compacted half-space to an applied load, either dynamic or quasi-static

[15]. Furthermore, the combined use of CCC roller data and spot-tests is an indirect method to control the site compaction through the roller measured stiffness moduli. The recent technical specifications of the CEN17006 European standard on Earthworks - Continuous Compaction Control (CCC) [16] provide a wide range of approaches to CCC and focuses on the calibration of data from vibrating rollers for quality control – quality analysis (Q_C/Q_A) purposes. The same standard can be used for CCC maximum compaction achievable and acceptance testing for weak area analysis. In this, the CCC data is considered for locating the poor compacted weak areas, which require further investigations by means of spot tests in order to assess the acceptance thresholds and limits of the weak zone.

Other than in CEN17006, the correlation of CCC data and spot tests can be found in different approaches in literature [9,12] because it has been proven that by taking into account the different depth of measurement of the measuring systems can help into obtaining correlations between sets of data recorded from roller and spot tests.

This study aimed to evaluate the compaction behavior and bearing capacity of a simulated rural pavement constructed in two layers of different recycled aggregates from a local plant. It was also aimed to investigate the optimal field conditions of recycled aggregates used in the construction of compacted foundation and base layers, while assessing the capabilities of testing devices employed to estimate the overall pavement bearing capacity. In parallel, the possible use of CCC data and spot test on recycled materials was targeted, with the final scope of proving their application both on unbound and bound layers.

2 Materials

Five different recycled aggregate mixes were used for constructing the two layers trial road. These were obtained from a high-quality C&D aggregates recycling plant, which produces CE marked aggregates to be used in various applications, including pavements. The amount of their floating elements is neglectable and three of them were well graded, which is more desirable for utilizing in pavement layers. The constituents of the experimental materials are listed in Table 1, and their particle size distributions are shown together with the envelope of an Italian road authority in figure 1. Additional physical and mechanical properties of the materials such as optimum moisture content (OMC), maximum dry density (MDD) and California bearing ratio (CBR) are given in Table 2.

3 Trial Field Layout and Compaction Process

The experimental road section was constructed by using the 5 mixes above described. The constructed road in the recycled plant was purposely subjected to the high-volume traffic of heavy trucks (at least 10 to 15 fully loaded 5-axles lorries per day). The existing subgrade of the pavement was constructed in the previous years with very thick layers of mixed recycled aggregates as a heterogeneous filling blends of CDW and clayey soils, hardened by the plant traffic of numerous vehicles including dozers and

Table 1. Characteristics of the used recycled materials.

Material	Short name	Constituents	Weight composition
Stabilized mix of Crushed Concrete and Reclaimed Asphalt	**ASFC**	1. Concrete-based building demolition rubble: industrial pavements, beams, pillars, etc. 2. Vineyard poles made of reinforced concrete 3. Asphalt slabs and Reclaimed asphalt pavement	– 50% Concrete – 50% RAP
Construction and Demolition Waste	**CDW**	1. non-selected building demolition rubble: brick, concrete, plaster, sand, cement, ceramics, etc. 2. Ceramic Tiles (ceramic industry waste) 3. Industrial waste (steel / foundry slag, sandblasting dust)	– 50% Demolition mix – 20% Ceramic waste – 30% Industrial waste
Stabilized Recycled Concrete	**RCA**	1. Concrete-based building demolition rubble: industrial floors, beams, pillars, concrete tiles, etc. 2. Reinforced concrete of Vineyard poles	– 100% Concrete rubble
Stabilized Crushed Concrete sleepers	**TRV**	1. Reinforced concrete of railway sleepers	– 100% Concrete rubble from sleepers
Mix of Crushed Sleepers and Foundry Waste	**MTRV**	1. Reinforced concrete of railway sleepers 2. Industrial waste (steel / foundry slag, sandblasting dust)	– 60% Concrete rubble from sleepers – 40% Industrial waste

excavators. Even though strongly compacted and very stiff, the subgrade surface was vibratory roller-compacted and assessed by spot tests before constructing the foundation unbound layer. An area 6.4 meters wide and 36.0 meters long was delimited for constructing the pavement by laying the selected recycled materials mixes. The simplified plan of the site and its layers are shown in Figure 2.

A 35 cm thick loose layer made of four recycled materials was laid and leveled on the area. Each section measured 9 meters in length and 30 cm in thickness were aimed for the unbound foundation layer. The layer was compacted in three parallel lanes by a 19 tons CCC roller set with constant vibration amplitude, frequency and speed. The subgrade and unbound base layer compaction and CCC proof-testing were performed by means of a BOMAG BW219 DH-5 compactor with a drum width of 212 cm. On each lane, 4 sets of forward vibrating and reverse static compaction passes were done and the stiffness data were simultaneously collected.

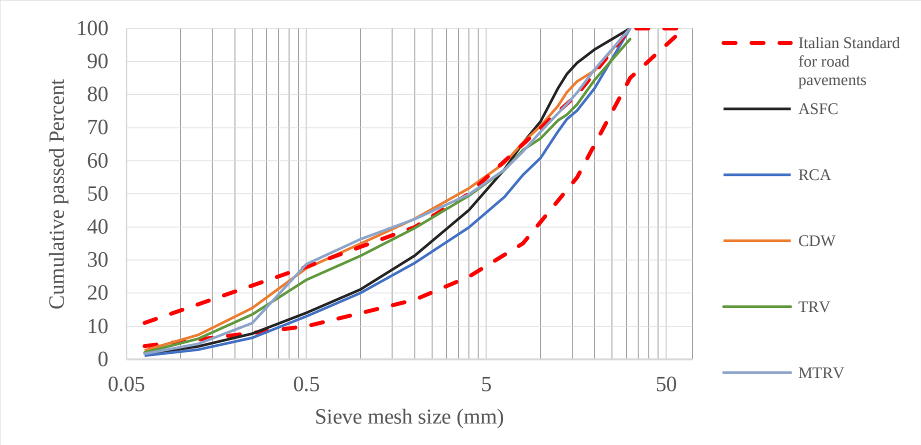


Fig. 1. Particle size distribution of the experimental recycled materials.

Table 2. Physical and mechanical properties of recycled materials.

Material	OMC (%)	MDD (kg/dm^3)	Un-soaked CBR (%)	Soaked CBR (%)	Los Angeles index (%)
ASFC	6.27	1.96	92	50	24
RCA	10.80	1.92	165	151	31
CDW	9.55	1.94	159	122	37
TRV	1085	2.00	202	295	29
MTRV	10.79	1.94	110	150	30

For the construction of the cement-bound layer, the recycled aggregates of MTRV (mix of crushed concrete sleepers and foundry waste) were mixed with cement and water and laid in a target 20 cm thick layer. A 3% Portland cement was added to the recycled MTRV and produced in-situ with an automatic BLEND E050 blending machine.

The cement-bound mix was laid over the unbound layer as shown in Figure 2. The section width of 3 meters was adopted in order to create 4 different layered pavement sections combining the cement-bound layer with the four different foundation materials. Vibratory CCC compaction was performed on the cement-bound material by means of a BOMAG BW174AP-4VAM roller.

The characteristics of the two compacting rollers are reported in Table 3.

3.1 Spot tests

Four regular grid sets of Plate load test (PLT), Lightweight deflectometry (LWD) and dynamic California Bearing Ratio (dynamic CBR) tests were done on the field layers in different days. The tests on the subgrade were done on the 9th of October 2020 before constructing the unbound layer, which was evaluated in two different days: a week after construction (23rd of October 2020) and after winter (22nd of March 2021). Moreover, twelve LWD and four PLT additional spot tests were performed on the cement-bound base layer over each section.

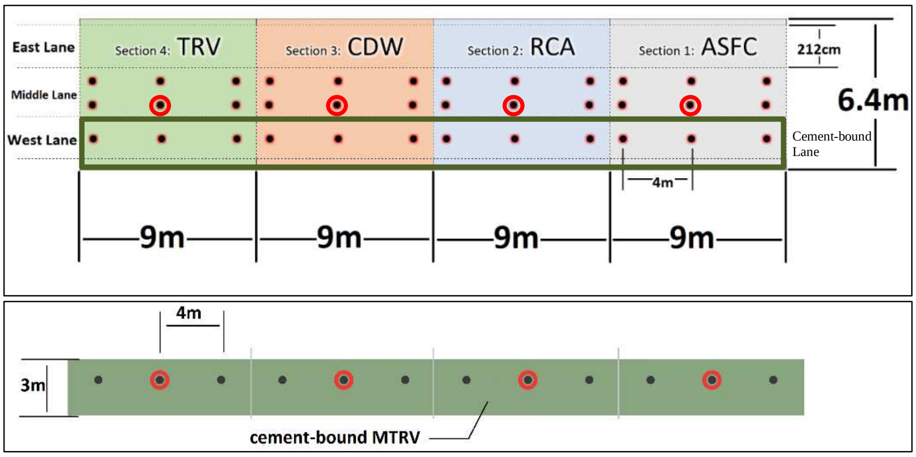


Fig. 2. Size of the unbound (top) and cement-bound (bottom) layers of the trial field. Locations of LWD - dynamic CBR (black points) and PLT (red circles) spot tests are shown. Compaction was performed from left to right both in vibratory and static mode (reverse).

Table 3. Specifications of roller compactors

Layer	Unbound foundation layer	Cement-bound base layer
Model	BOMAG BW219 DH-5	BOMAG BW174AP-4 VAM
Mass	19400 kg	9500 kg
Drum width	212 cm	170 cm
Linear load	60.1 kg/cm	29.8 kg/cm
Roller speed (average)	3.7 km/h	2.4 km/h
Vibration frequency	24 Hz	45 Hz
Manual Amplitude	1.2 mm	0.9 mm

4 Results and Discussion

4.1 CCC Data

A set of E_{vib} data was recorded on three compaction lanes of the foundation, namely: east, middle and west. Data are shown in Figure 3.

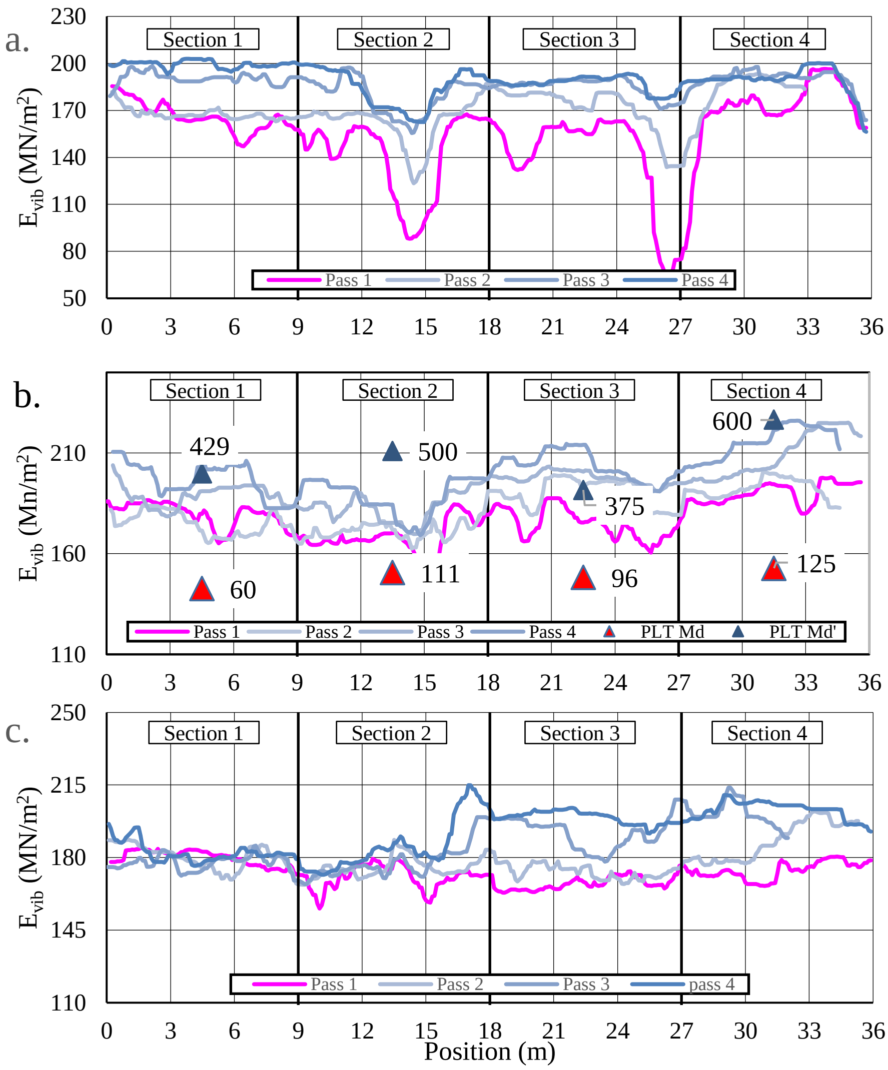


Fig. 3. E_{vib} modulus of unbound base layer: a) East Lane, b) Middle Lane, c) West Lane, Section 1: ASFC, Section 2: RCA, Section 3: CDW and Section 4: TRV. The values of PLT test in first and second cycle of loading (M_d and $M_{d'}$) are shown in the graph of middle lane.

The bold vertical lines show the adjacent sections. All graphs follow similar patterns, considering the subgrade stiffness inhomogeneity and differences in the materials of each section. Secondly, the values of E_{vib} increase with the number of rollers passes.

The E_{vib} increment in the experimental sections are markedly different. For the cement-bound layer, the distribution of E_{vib} graph increments is not constant between passes as shown in Figure 4. The final passes have similar E_{vib} values and the graphs of the final passes become more entangled. The total number of passes on the cement-bound layer is 6, which is more than the 4 passes made on the unbound layer. No further increase in E_{vib} values of the cement-bound base layer was expected with those drum settings. Evidently the cement-bound materials reach their compaction limit through a specific roller compaction energy and after four passes [17].

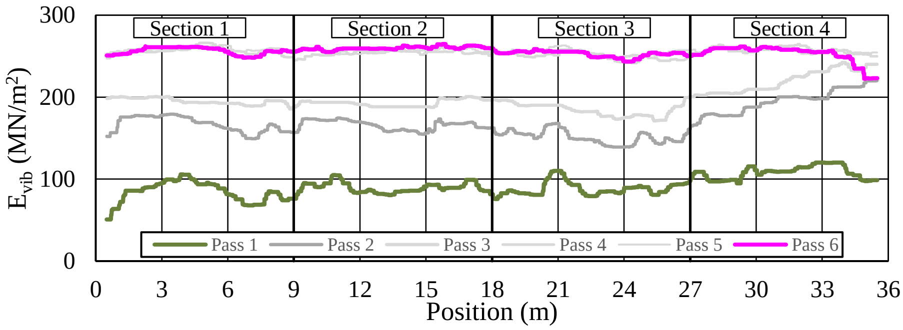


Fig. 4. E_{vib} values from the MTRV cement-bound base layer.

4.2 Densitometry

Densitometry tests were done on the different sections of experimental site in order to evaluate the changes in the Degree of Compaction (DOC) of the recycled materials under the vibrating roller action (Table 4). Most of the materials have an improved DOC after winter, which is more likely due to the heavy traffic over the unbound layer during the winter period. The DOC improvements of the CDW and RCA sections were more evident, as they almost reached full DOC at the end of winter. For crushed concrete sleepers (TRV) the improvement was minimal, as the autumn level of compaction was already very high. The ASFC section did not exhibit a similar increase and the reliability of the after-winter measured value was in doubt as the testing spot was falling in between the wheel tracks.

Table 4. Degree of compaction for subgrade and different sections of unbound layer before and after winter.

Sub-grade	Unbound layer	ASFC	RCA	CDW	TRV
91.8 (%)	Fresh state compaction	101.8%	88.1%	94%	100.1%
	After winter compaction	90.8%	97.9%	98.6%	100.4%

4.3 PLT Tests

Plate load tests were performed based on the Italian standard to assess the load bearing capacity of the pavement layers [18]. The ratio of the deformation moduli from PLT test (Table 5) shows the variation in bearing capacity from the first (M_d) and the second cycle (M_d') of loading. A low value of M_d/M_d' shows a residual compacting action provided by the first load cycle. The subgrade is clearly well compacted, while the winter traffic, despite the climate effects on the pavement, has generated a stiffer pavement. This is shown by the variation of M_d in time.

The lowest M_d/M_d' ratio in unbound fresh layer is for ASFC section, showing that PLT test could cause a compaction in the first cycle of loading. Overall the final bearing capacity of the trial site tends to be more homogeneous with the construction of the foundation layer and the action of cold climate and traffic seems not to have negatively affected the recycled aggregates single layer pavements, so far.

Table 5. Deformation modulus and settlements of PLT test for different sections of unbound layer.

		Md (N/mm2)	Md' (N/mm2)	Md/Md'	Settlement (mm)
Section 1 (ASFC)	Subgrade	97	250	0.38	1.22
	Fresh unbound	60	428	0.14	1.44
	After winter un-bound	143	428	0.33	0.49
Section 2 (RCA)	Subgrade	93.7	500	0.19	1.22
	Fresh unbound	111	500	0.22	0.94
	After winter un-bound	158	750	0.21	0.52
Section 3 (CDW)	Subgrade	150	375	0.40	0.88
	Fresh unbound	97	375	0.26	1.13
	After winter un-bound	200	750	0.27	0.48
Section 4 (TRV)	Subgrade	250	500	0.50	0.85
	Fresh unbound	125	600	0.21	0.82
	After winter un-bound	120	428	0.28	0.58

One PLT per each section was performed on the cement-bound layer, 1 day after construction (Table 6). The layer shows uniform results through the pavement sections, clearly demonstrating the positive effect of constructing a layered system topped with a cement-bound recycled material. Moreover, the bearing capacity contribution of the 20 cm cement-bound layer, although not fully cured, is proven and can justify the design of two-layered structures for heavy loads rural roads. The M_d/M_d' ratios have reached values in line with those obtained for the original subgrade that was made of few meters of well-compacted and weathered recycled materials.

Table 6. Deformation modulus and settlements of PLT test for different sections of cement-bound layer.

	M_d (N/mm^2)	M_d' (N/mm^2)	M_d/M_d'	Settlement (mm)
Point 1	167	750	0.22	0.57
Point 2	200	400	0.50	0.57
Point 3	200	428	0.47	0.48
Point 4	150	316	0.47	0.58

4.4 LWD Tests

The LWD test results of subgrade and unbound foundation layer are shown in Figure 5. Similar to PLT data, the subgrade shows inhomogeneities in stiffness along the trial site length and width as shown by LWD tests done on the 9th of October. LWDs on the subgrade are very high and they include some peaks above 150 MPa, confirming that a solid compacted surface existed in the trial site area. In principle, this condition could well represent the actual conditions found on a trafficked rural road made of pre-existing unbound materials.

With the addition of the foundation layer, in various sections, the E_{vd} values become more homogeneous within each section, while the differences among the recycled materials are evident, more in the fresh state, than in the after-winter one. In March, the TRV section appears (also visually) to be stiffer in terms of LWDs. Lower values have been recorded for sections ASFC and RCA. Nevertheless, the feasibility and positive effect of utilizing recycled materials in pavement layers of rural roads is proven as they can bear traffic and weather over a full rigid winter.

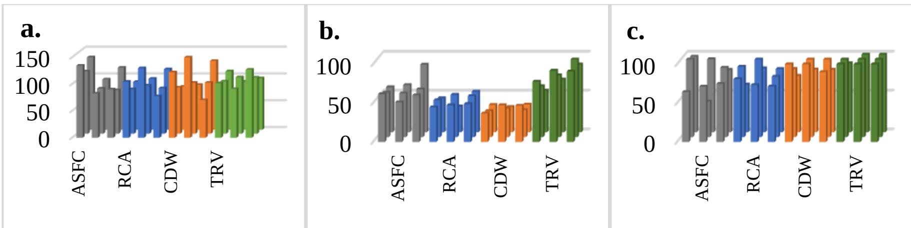
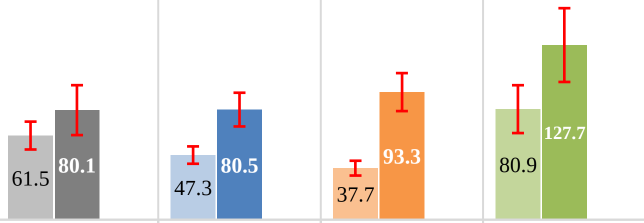


Fig. 5. Measured LWD values (E_{vd} in MN/m^2): a. Subgrade, b. Fresh unbound layer, c. Unbound layer after winter.

Based on average values listed in Table 7, it is evident that despite TRV and ASFC recorded the highest E_{vd} in fresh compacted state among the considered recycled materials, their higher standard deviation show that they have higher dispersion and more inhomogeneity. The other important observation is the stiffness improvement of the unbound layer after winter. The largest increase was measured on the CDW section, although the layers surface appeared rougher and with more surface ruts than other sections.

Table 7. LWD average values (MN/m²) and standard deviations in different trial site sections.



	(ASFC) Section 1	(RCA) Section 2	(CDW) Section 3	(TRV) Section 4
Fresh unbound	61.5	47.3	37.7	80.9
Standard Deviation	10.2	6.4	5.4	17.5
After winter	80.1	80.5	93.3	127.7
Standard Deviation	18.3	12.3	13.9	27.0
Increase (%)	0.3	0.7	1.5	0.6

In the cement-bound base layer, the stiffness considerably increased after 7 days. Results are shown in Figure 6 where fresh data are directly compared with cured ones, after one week when the layer surface was purposely wetted for cement hydration (no traffic). Bearing in mind the underlying foundation materials (see Figure 2), the overall bearing capacity of the simulated rural pavement reached consistent and high values of E_{vd} when the 50 cm double layered pavement is constructed. Considering the evolution of stiffness of the foundation unbound layer, the design of the road should also be taken into account that the construction of the cement-bound layer, when needed, can be slightly delayed in time, without compromising the functionality/integrity of the unbound pavement.

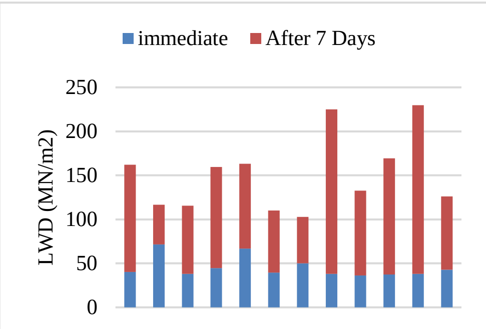


Fig. 6. LWD stiffness values (MN/m²) of the cement-bound layer.

Correlation of Dynamic CBR and LWD Test Results

Dynamic CBR tests were performed on the same spots as LWD tests. The CBR device is easily assembled and makes use of the same 10kg falling weight, rod/handle, spring sets and acceleration sensor of the LWD equipment. A 5 cm diameter piston is placed on the testing surface and a single blow is applied after assessing good contact and surface homogeneity below the piston. Although the measurement of LWD values and dynamic CBR are based on the same measuring system, studying the correlation between their values can be useful for Q_C/Q_A purposes and combined spot test measurements on compacted layered systems. CBR measured values are upper-limited to 200%, which makes it impossible/unreliable to measure the bearing capacity of stiffer surfaces due to the possible measurement fail for very low settlements on very stiff layers. The graphs in Figure 7 show that a correlation exists between dynamic CBR and LWD values, however, it becomes weaker as dynamic CBR values approaches the upper limit. It is evident that the group of points indicating the results of fresh unbound layer (dashed ellipse) are better correlated than the points related to stiffer after-winter layer data. For high LWDs the dynamic CBR values appear less consistent and the correlation is gradually lost. For the tested materials and thicknesses, CBR values above 140-160% progressively lead to lower quality of the correlation, despite the dynamic CBR upper limit is set to 200%. The dark ellipse shows some data obtained in the after-winter measurement. These are the weakest points where the LWD-dynamic CBR correlation can still considered to be valid. In summary, the use of dynamic CBR on granular recycled materials seems to be well correlated with the corresponding LWD measured values, provided that the CBR values are well below the device upper limit.

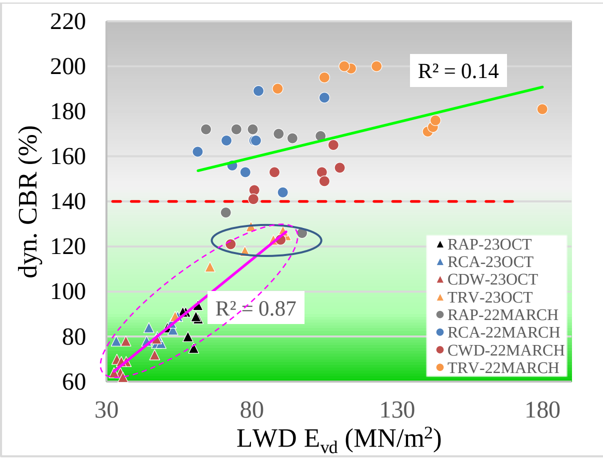


Fig. 7. Correlation of LWD and Dynamic CBR test results from fresh and after-winter unbound layer.

Correlation of Spot Tests and Roller CCC Data

Table 8 shows the squared correlation coefficient of LWD (E_{vd}) data and the corresponding E_{vib} extracted from the CCC graphs obtained during compaction of the unbound layer in the position of the spot tests. For the middle lane of roller compaction, two sets of LWD tests were done on the left and right side of the roller lane width. For the west lane, the row of LWD spots was centered on the roller lane. The main reason behind this was to evaluate the effect of spot test location relative to the drum position on the correlation of the LWD-CCC data.

The correlation values between the last CCC pass on unbound layer with the underlying subgrade LWD tests are higher than the correlation of first pass with same LWD results. This shows that on the initially loose recycled materials, the CCC measurement detects the superficial inconsistency of the layer and the drum action is employed mainly for the material compaction, limitedly probing the stiffness of the subgrade. While, when the layer is more compacted, the drum is able to extend its measurement depth and sense the subgrade stiffness. It should be noted that the CCC measurement depth is higher than the compaction depth. The 1.2 mm amplitude drum setting is certainly exceeding the 30 cm thickness of the unbound foundation, reaching the compacted subgrade. The zone of influence and depth of sensing for LWD test is often considered to be 1.5 to 2 times the diameter of the LWD plate, which would be ranging from 45 to 60 cm. With these measuring depths, the LWD-CCC correlations are very likely to be valid.

Table 8. LWD-CCC correlation values for different zones of the foundation unbound layer.

R^2	Last pass CCC			1st pass CCC		
	Mid		West	Mid		West
	Left	Right		Left	Right	
Subgrade	0.56	0.60	0.17	0.30	0.20	0.58
Fresh unbound layer	0.78	0.58	0.85			
After winter unbound layer	0.73	0.18	0.62			

Considering the CCC sensor position (left side of the drum) the better correlations with the left side LWDs seems to be justified: this is particularly true for the measurements on the fresh unbound layer, with reference to the Last pass of roller. The consistent correlation of CCC and LWD spot tests shows that LWD test could be applied to recycled pavements as a supplementary quality control method and the assessment of vibratory compaction required for optimum compaction in order to achieve the targeted bearing capacity. Becoming stiffer and more compacted after winter, the correlation of after winter LWD test values with last pass off CCC, decrease slightly, showing that the localized densification due to the truck tires post-compaction could change the local stiffness patterns of the pavement.

The correlation between E_{vib} values of the cement-bound layer and their corresponding LWD tests are shown in Table 9. The correlation on the freshly compacted material is higher than that obtained after seven days of curing, which provides a hint on the effect of cement hardening on the possible use of correlations for Q_C/Q_A purposes. In short, the hardening mechanism of cemented materials in cement-bound layers, can alter the stiffness pattern of the layer and the consequent correlation. The partially hardened MTRV cement-bound layer has already a very high load bearing capacity, thus shifting the layer toward behaving more like a rigid one.

Table 9. Correlation coefficient squared values of cement-bound layer and spot tests.

R2	Last pass CCC
After winter unbound layer	0.00
Cement-bound fresh	0.59
Cement-bound after 7 days	0.16

Coupling the CCC and LWD Measurements

In line with the previously mentioned European Standard on the use of CCC data for in situ testing and assuming LWD threshold values of 50 MN/m^2 for the unbound foundation layer and 70 MN/m^2 for the cemented base layer, the obtained corresponding E_{vib} values of 190 and 260 MN/m^2 will give to hand consistent criteria of roller compaction quality control. This process could be also repeated considering the different sections of the unbound layer independently. This will give an insight towards the dissimilarity in the behavior of different mixes of recycled aggregates in field compaction. It shows that the CDW mix requires higher CCC threshold (214 MN/m^2) than others, which have very similar threshold E_{vib} values (approx. 190 MN/m^2).

When analyzing the CCC threshold obtained from LWD data and E_{vib} values measured on the cement-bound base layer, it should be kept in mind that the compacting roller is different (lighter and with different settings) than the one used for the foundation layer. Furthermore, the correlation is now affected by the layered system where the lighter roller compactor will more likely sense the new pavement and the very stiff top part of the subgrade (amplitude set to 0.9 mm). In the light of the above, higher E_{vib} values are expected for intermediate LWD values.

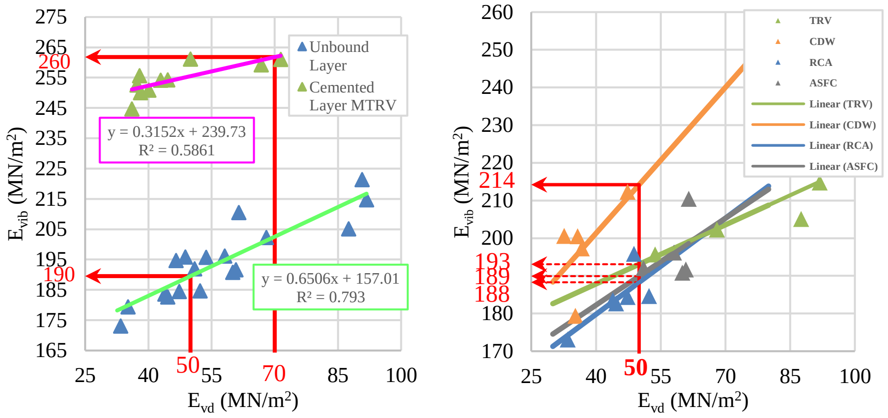


Fig. 8. Correlation of stiffness values obtained from CCC and LWD data: Left: all unbound and MTRV cement-bound layer, Right: Different sections of unbound layer.

Considering the calculated limits on the CCC graphs of the last passes as shown in Figure 9, it is clear that different materials have different sufficient pass numbers with the applied roller settings. ASFC and TRV could achieve the limit by four passes while

RCA would need additional passes to satisfy the criteria. Section 3 meets the unbound layer threshold in four passes, however as the individually calculated threshold for CDW mix is higher than the general value (214 MN/m^2), it may need some additional passes for fulfilling the 50 MN/m^2 stiffness value.

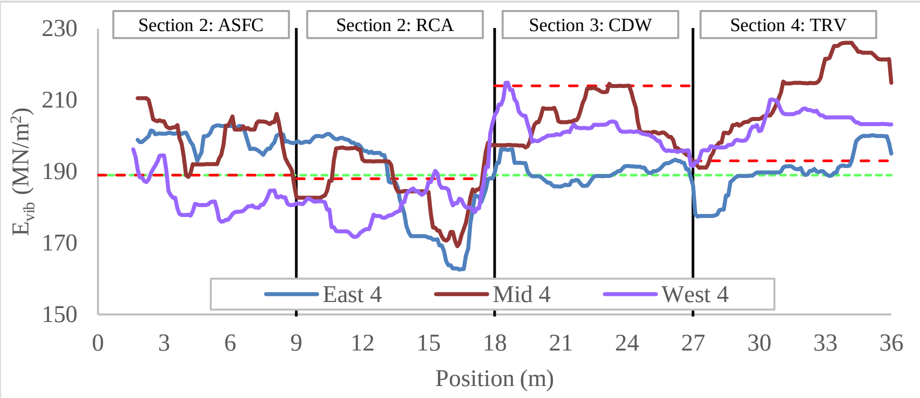


Fig. 9. CCC last passes with averages (red dashed lines) for 3 lanes of unbound layer with the threshold of E_{vib}=190 MN/m^2 (green dashed line), corresponding to E_{vd}=50 MN/m^2 from LWD.

5 Conclusions

It was shown how recycled aggregates from construction and demolition wastes can be utilized effectively in constructing low-traffic rural and farm roads in the form of single or multiple unbound or cement-bound layers. This application could have an important contribution in moving towards circular economy and sustainability in agriculture and rural transportation infrastructure.

This paper specifically tried to investigate the behavior of different mixes of recycled aggregates obtained from civil engineering activities in unbound and cement-bound layers of a trial pavement, by recording the modulus from CCC vibrating rollers used for compacting the layers, and comparing the results with various spot tests done before and after the construction of each layer. A wide set of recycled aggregates with different constituents were used for constructing a heavy load low-traffic experimental road with unbound and cement-bound layers. The used recycled materials showed improved density, settlement and mechanical properties such as stiffness, after being compacted and also some progressive properties by increasing the passes of vibrating roller.

The CEN17006 European standard suggested procedure for correlating CCC with spot test was used to simulate Q_C/Q_A of recycled layers. Furthermore, an uncommon spot test (dynamic CBR) was applied to evaluate the correspondence with other largely available tests, such as LWD.

The acceptable correlation between spot test results and measured values from CCC data, could be used for assessing the level of compaction in terms of roller passes for each type of recycled material. Based on this method, it was shown that different recycled mixes may need different number of passes to meet the spot test threshold.

The dynamic CBR test could also play an alternative role to LWD test in freshly constructed layers with less stiffness than hardened layers, as the LWD-CBR correlation can be lost on very stiff layers. Hence, dynamic CBR could also contribute in quality control purposes of layers constructed by means of CCC technologies.

The trial site unbound foundation layer was subject to real traffic and winter weather condition for several months. Although a reduction in mechanical properties could be expected after traffic and cold wet climate, an improvement of bearing capacity was recorded after a full winter period. A post-compaction of well graded materials could be the reason of such an improvement, which indirectly proves that these recycled materials could be successfully applied for unbound layers of rural pavements without the use of surface sealants. Nevertheless, the improvements in properties of diverse compacted mixes were different, which could be related to their components and should be considered in pavement design, especially when some residual pozzolanic effect could be exploited through the recycling process.

Acknowledgment

The authors acknowledge the Italian companies of C.A.R Inerti srl. and BOMAG Italia srl. for providing materials, technicians and necessary machinery for experimental field operations of this research.

Conflicts of Interest.
The authors declare no conflict of interest.

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APPENDIX: ADDITIONAL PICTURES RELATED TO CHAPTER 4

Left: The subgrade of trial field. Right: Performing PLT test on subgrade soil.

Left: Trench dug of the subgrade. Right: Sand Cone Densitometry test.

Left: The recycled aggregates carried and hauled for constructing unbound layer. Right: Grading and levelling of unbound material.

The roller compaction of unbound layer.

Left: The BLEND machine for in-situ production of cement-based material. Right: Compaction of cement-bound layer.

LWD testing between roller passes.

Left: The monitoring of continuous compaction control system of the roller. Right: Final surface of cement-bound layer.

CHAPTER 5: SUSTAINABLE SINGLE MIX, COLD-APPLIED SEMI-FLEXIBLE COMPOSITE LAYER FOR SPECIAL RURAL PAVEMENTS

FOREWORD

In this chapter, after introducing the semi-flexible pavements as a valid surfacing for heavy load low-traffic rural and farming pavements, an affordable and clear-cut alternative method is presented for the production of the bitu-cementitious material. Semi-flexible pavements (mostly known as grouted macadams) despite having some good and unique properties such as high strength and good chemical resistance, have as major drawback the required two-phase construction method that involves the laying of a hot mix porous asphalt. In the traditional application, in fact, these are consisted of a highly porous asphalt skeleton filled with fluid low-viscosity cementitious grouts. The problems related to the precise grading of the aggregates for the creation of the porous skeleton hinders the use of recycled aggregates from reclaimed asphalt pavements (RAP) for the construction of the hot mix asphalt porous layer. Also, the viscosity of the cementitious grout is of outermost importance for a successful grouting and often poses difficulties on site. In the proposed innovative solution, RAP aggregates are directly mixed with the right volumes of cementitious slurry and a special cold bituminous emulsion is used as binding agent, to make the production and laying process more sustainable. Laboratory optimizations of the mix volumetric shows how the mechanical behaviour of the resulting material is highly influenced by the reciprocal proportion of the bituminous and cementitious phases. A full-scale trial site is foreseen and will prove the feasibility of the proposed green solution on a monitored fully-recycled trial site.

The research work is presented in the following paper:

Pourkhorshidi S., Solouki A., Torreggiani D., Tassinari P., Sangiorgi C. Laboratory characterization of bitu-cement composite recycled cold mixes as an alternative to traditional semi-flexible pavement layers. Case Studies in Construction Materials (to be submitted in 2023).

Authorship declaration

A summary of each author’s contribution to this work is provided below.

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Laboratory characterization of bitu-cement composite recycled cold mixes as an alternative to traditional semi-flexible pavement layers

Abstract

The present study aimed at the preliminary investigation for the feasibility of producing bitu-cement composites layers containing 100% Reclaimed Asphalt Pavement (RAP). For this purpose, a specific composite binding phase was created by combining a special commercial cementitious grouting mortar with a cold-mix latex-modified bituminous emulsion. In view of a real scale industrial application, the RAP aggregates were supplied from a recycling plant into a coarse and a fine batch. To meet the targeted envelope for the granulometric distribution, the RAP aggregates were used in a 50-50% proportion. The samples were laboratory produced and gyratory compacted and underwent simple screening physical, mechanical and dynamic testing including indirect tensile strength (ITS) and indirect tensile stiffness modulus (ITSM). As expected, the ITS results indicated that higher amount of cementitious phase increased the stiffness of the mixtures, whereas the addition of bitumen produced more ductile specimens. Cement to water ratio and aggregate volume portion seem to have the least effect on the mechanical properties of the obtained mixtures. The mechanical data show how the proposed alternative can be promising and confirms the feasibility of using such a single-mix semi-flexible pavement containing high RAP quantities to be further investigated through field and full-scale industrial testing.

INTRODUCTION

The growth of roads construction and the consequent maintenance interventions is posing the global supply of natural resources under discussion as the main sustainability goals are directed to recycling instead of depleting. Annually, aggregate production plants produce about 3000 million tons of non-renewable natural aggregates globally including vast quantities of waste and by-products [1]. In the past, due to the use of traditional linear consumption strategies, waste by-products have been often dumped and landfilled, giving rise to potential environmental and safety issues. Statistical reports indicate that about 48% of the construction and demolition (C&D) waste in UK is related to mineral by-products [2]. The incorporation of waste materials into flexible and rigid pavements could decrease the demand for virgin natural aggregates. This would be in line with the new economic cyclic flow model [3]. For instance, various studies have put the recycled quarry waste into asphalt and concrete pavements category [4–6].

Prevention and reuse are at the top of the waste management hierarchy [2], where it is suggested to use less natural resources in the design and manufacturing stages. Coupling it with the fact that recycling waste material into pavements could only reduce the use of natural aggregates to some extent, researchers have moved towards minimizing or zeroing the produced waste and reduce the need for new aggregates. Among existing methods, reusing different layers of pavements could be a sustainable, fast and viable approach. Asphalt pavements incorporate great values as they are produced with approximately 95% virgin aggregates. At the end of their service life, the asphalt material is removed from the surface and is identified as Reclaimed Asphalt Pavement (RAP). This material is 100% recyclable [7,8], which could produce zero-waste during repair and maintenance of road pavements in a perfect circular economy approach. Various researchers have investigated the use of 100% RAP [9,10], the application of various rejuvenators [11] and their mechanical performances [12]. Moreover, the feasibility of combining warm mix asphalt and high percentage of RAP has been studied [13]. However, due to various parameters such as RA aggregate quality, available plant technology, proper mix design and the performances of the final mix containing RAP, the increase of RAP content in HMA and WMA has been often limited [14,15]. In most European countries, approximately 90% of RAP is reused. However, this does not imply that RAP has been applied within the surface layer of the pavements. According to literature and existing data, 8.4% by weight of the RAP in Europe is stockpiled, and up to 20% is down-recycled as aggregates in unbound layers [8,14].

However, various approaches have been proposed by researchers that allow the increase of RAP in pavement surface mixtures. For instance, studies have shown that crushed concrete and RAP could also be recycled into concrete/rigid pavements [16]. For instance, up to 50% of virgin coarse aggregates were replaced with RAP, where the durability of the produced concrete pavement was studied in terms of chloride permeability, the freeze-thaw durability, and the coefficient of thermal expansion [17]. The authors claimed that a high-strength concrete mixture was required for achieving sufficient durability.

In a different attempt, the feasibility of using RAP as virgin aggregate to produce cement treated based materials was studied [18]. The data showed that mixtures containing 70% RAP as virgin aggregates outperformed conventional mixtures. Recently, the potential of using RAP in cement concrete pavements has been dully reviewed [19].

In general, concrete-bound and bituminous-bound mixtures are used for road construction. Each approach has its own pros and cons, which has led researchers to investigate the possibility of combining the two solutions. Problems such as joint constructions and thermal expansions in concrete slabs as well as rutting and shoving/corrugation in continuous bituminous mixes due to dramatic increase in traffic loading, volume and weather severity have imposed to road directorates worldwide large expenditures each year [20]. These serious challenges become notable in critical service conditions of roads and give prominence to more effective methods and materials for the construction and maintenance of pavements. Semi-flexible (grouted macadam) pavements have attracted many attentions in recent years as they are a valid compromise towards the drawbacks of the traditional pavements. They are consisted of porous asphalts mixes with considerable inter-connected air voids that are filled with special fluid grouts, i.e. mostly resin-cementitious pastes. Implementing this peculiar wearing course, provides a proven solution against permanent deformations, which is a typical issue of conventional hot mix asphalts (rutting and shoving). This is because of the high load bearing capacity of the composite material and its outstanding stiffness and durability in harsh conditions, and the considerable fatigue life in comparison with standard asphalt layers [21]. This advantage is achieved in a continuous jointless pavement with elevated surface quality, which can also provide better skid-resistance properties than concrete pavements [22].

In the proposed research, in order to fully develop a semi-flexible pavement containing high quantities of RAP a number of limitations have been primarily acknowledged: above all the need for a specific RAP size distribution. The porous skeleton of common grouted macadam pavements is made of open-graded asphalt mixtures, which require precise grading of aggregates to provide the 25% of interconnected air voids. Reaching such gradation can be very challenging when using RAP materials, especially if HMA or WMA are produced. In fact, RAP aggregates change size during the hot mixing phase because of the separation of particles inside the RAP clusters. Thus, the precise aggregate size envelops are difficult to control for achieving the target porosity and permeability of the required lithic skeleton. Furthermore, the grout fluid must have a sufficiently low viscosity to be used as grout and fill the voids of the porous skeleton by gravity force. This causes some limitations to the composition, producing procedure, added fillers and chemical additives, and laying temperature of the grouting [20,23]. Finally, producing the porous asphalt skeleton of the traditional grouted macadam pavements using cold bituminous binder, although feasible, could be challenging in real construction sites as the variability of RAPs and the use of emulsions may hinder the creation of a real porous structure. These limitations are constraints, along with the costs, to the diffusion of semi-flexible pavements, especially when the use of high quantities of RAP is foreseen.

An alternative solution for the production of composite semi-flexible admixtures could be the direct mixing of cement paste and bitumen emulsion in a cold binding matrix that would allow the use of high quantities of RAP in cold applications. A recent case study compared a cement treated RAP containing bituminous emulsion with a standard flexible pavement [24]. In a similar case, the authors indicated that the addition of cement to 100% RAP bituminous emulsions could improve the mixture’s susceptibility towards moisture damage, while enhancing its rutting and fatigue resistance [25].

In this research, the bitumen-cement bound semi-flexible composite is produced without making a porous skeleton, to allow the use of large quantities of RAP materials. The cold mixing asphalt and cement paste provides the possibility of using a well-graded RAP aggregate, which can eventually cure and lead to mechanical properties similar to those of a two-phase produced grouted-macadam. However, only very few publications have reported attempts of recycling RAP in such a method to improve the sustainability of traditional grouted macadams. This will have important sustainability improvements toward employing the recycled asphalt aggregates, together with many technical advantages due to use of cold bituminous emulsion binders. Mixing all the components in a direct single phase will lead to the formation of a binding matrix composed of cement and bitumen, which implies the existence of phyco-chemical reactions and developed bonding at their interface.

MATERIALS AND METHODS

High quality and EC marked RAP (Table 1) complying with EN standards was obtained from a local recycling plant in Imola (Italy). The supplied RAP was provided in two main batches of coarse (4-14mm) and fine (0-8mm) sizes having the gradations shown in Figure 1. The selected aggregate size distribution was obtained by mixing the coarse and fine aggregates in a 50-50% weight proportion. This allowed to achieve the closest distribution to a well-graded envelope and keep the plant production operations simple. The special cement used for the cementitious paste was provided by CVR srl, Italy; whereas a latex modified cold mix emulsion was locally designed for RAP recycling and produced by Valli Zabban S.p.A, Italy. The properties of cement and bituminous emulsion are shown in Table 2 and Table 3, respectively.

Table 1. Properties of RAP aggregates.

	Fine	Coarse
Size range (EN 933-1)	0-8mm	4-14mm
Proctor Fragmentation test*	19.5%	6.8%
Los Angeles fragmentation (EN 1097-2)	22%	14%

**Based on non-standard method defined by RILEM* [26].

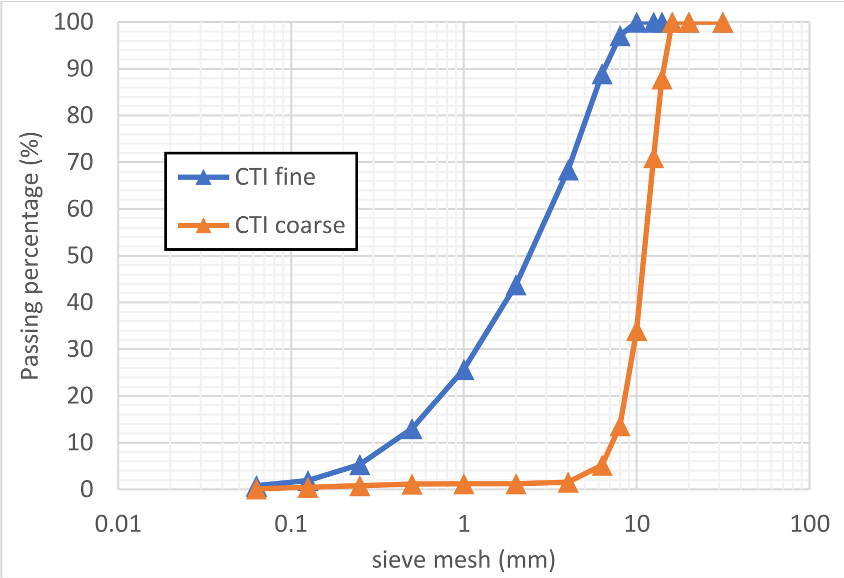

Figure 1. Aggregate size distributions of two RAP batches (EN 933-1).

Table 2. Properties of the special cement for grouting.

Powder size range	(EN 206-1)	0-500 microns	
Powder density	(EN 206-1)	1250 kg/m^3	
Slurry live time	(EN 196-3)	60 min	
Slurry hardening time	(EN 196-3)	Start: 60 min, End: 90 min	
Slurry density	(EN 12350-6)	Fresh	1950 kg/m^3
		Hardened	1750 kg/m^3
Average flexural strength	(EN 12390-5)	7 days	6.5 N/mm^2
		28 days	10 N/mm^2
Average compression strength	(EN 1015-11)	7 days	25 N/mm^2
		28 days	45 N/mm^2
Compression elastic modulus		22 GN/m^2	
Average adherence strength (fu)		28 days	1.5 N/mm^2

Table 3. Properties of the latex modified cold mix emulsion.

Binder content	(UNI EN 1428)	> 60%
Water content	(UNI EN 1428)	< 40%
pH	(UNI EN 12850)	2 – 4
Stability with cement	(UNI EN 12848)	< 2%
7 days sedimentation	(UNI EN 12847)	< 10%
Viscosity at 40° C	(UNI EN 12846)	15 – 70 sec
Penetration (25° C)	(UNI EN 1426)	50 – 70 dmm
Softening point	(UNI EN 1427)	> 55° C
Fraass breaking point	(UNI EN 12593)	> -10° C
Elastic return (25° C)	(UNI EN 13398)	> 55%

A composition similar to the usual grouted-macadams was considered (12% bituminous emulsion and 15% cement on the weight of whole mix) as reference sample. Several mixtures were produced by varying the cement and emulsion volumetric proportions ranging from 11 to 19% and 6 to 18%, respectively. The cement to water ratio and RAP amounts were varied accordingly to produce different dense mixtures as listed in Table 4. The cement slurry paste was produced by mixing water and cement at specific ratios. The obtained paste was then added to the graded RAP and mixing was applied for homogenization. Finally, the cold bituminous emulsion was added to the mixture. The specimens were manually mixed then and compacted by means of a standard gyratory compactor with 100 mm diameter moulds. A total of 50 cycles was applied to each specimen during compaction taking example from the literature. The produced samples were stored and cured unsealed at room temperature and tested 7 days after production.

Table 4. Mixture design range of constituents for the experimental bitu-cement mixtures.

Material	%
Bitumen emulsion	6 ,9, **12**, 15, 18
Cement powder	11, 13, **15**, 17, 19
Aggregate	70, 73, **76**, 79
cement/water ratio	2.5, **3**, 3.5

**Bold numbers refer to the reference mixture*

Static and dynamic tests were used to investigate the developed mechanical properties of the samples. For each mix design, six samples were produced using the above-mentioned procedure. The indirect tensile strength (ITS) test was carried out on each specimen applying a constant displacement of 50 mm/min (EN 12697-23). The maximum failure load was then used to calculate the ITS value. The indirect tensile strength modulus was obtained based on EN 12697-26 Annex C standard. Samples were tested at the temperature of 20°C, where each sample was conditioned for at least 4 hours prior to any testing.

RESULTS AND DISCUSSION

Geometrical and physical properties

The maximum densities of the samples were calculated by EN-12697-5 standard, based on the measured maximum density of components, including aggregate, hardened cement and bitumen binder. The bulk densities of the samples with different compositions were calculated based on EN12697-6 procedure for cylindrical specimen. These numbers were used for void percentage calculation of the samples made with diverse recipes, as shown in Figure 2. The absolute cementitious and bituminous phase portions in the final samples were calculated and also demonstrated parallel to the emulsion and dry cement percentages of recipe. Due to lower density of bitumen comparing to other constituents, it is evident that increasing the portion of bitumen reduce the bulk density of specimen. Moreover, the voids content decreases by adding emulsion (binder), while there is a peak in voids content by increasing the cement portion in recipe. This could be due to complicated water loss mechanism of the various compositions during compaction and curing.

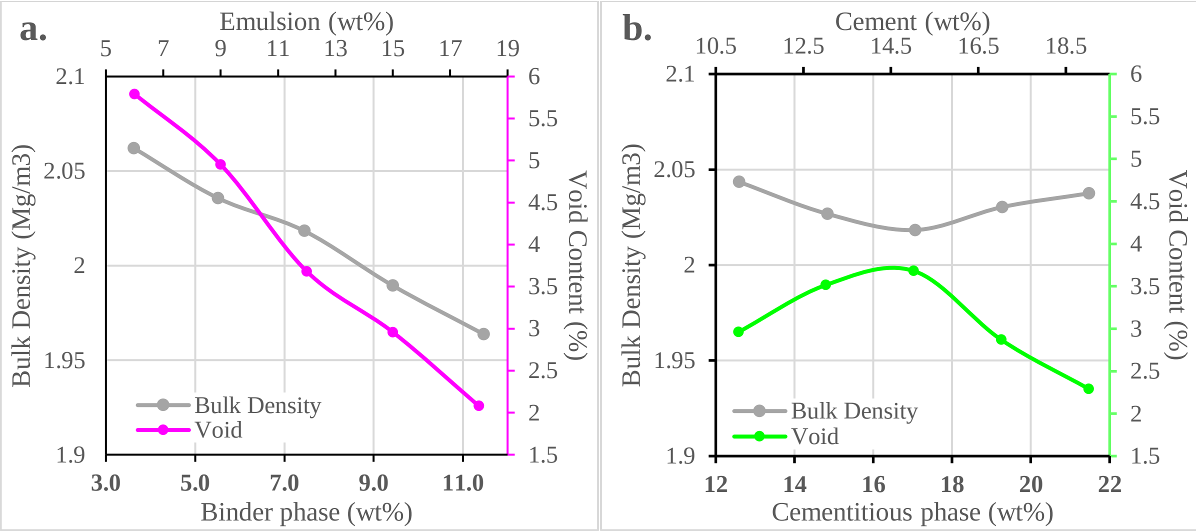

Figure 2. Change in void content of specimen a. By increasing designed emulsion content (and bituminous binder content), b. By increasing designed cement content (and actual cementitious phase percent in final specimen)

Mechanical Properties

The compacted reference mix has undergone ITSM test at different temperatures of 10, 20 and 30°C after long-term curing in room temperature, and the results are displayed in Figure 3. As expected, the modulus decreases at higher temperatures; here, from 10 to 30 the ITSM decreased around 45%.

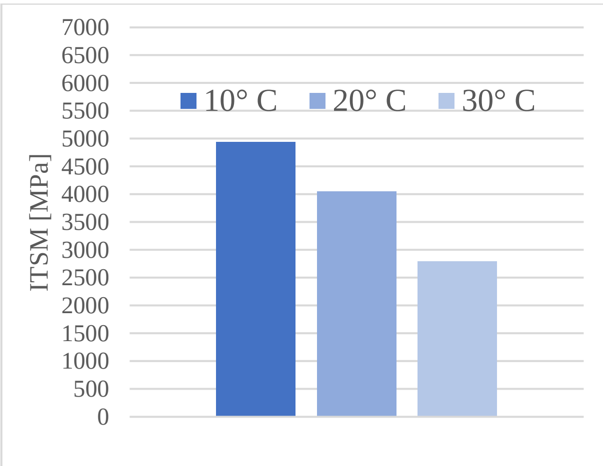

Figure 3. Indirect tensile stiffness modulus of the reference composition sample at different temperatures.

The effect of different emulsion percentage on the mechanical performance of the bitu-cement specimens is presented in Figure 4. A linear drop in terms of strength is observable with an increase in emulsion content. For instance, the highest ITS value of approximately 0.88 MPa was recorded when 6% emulsion was added to the mixture. However, this value dropped by 77% when up to 18% of emulsion was used. The ITSM values followed a similar behavior. The data show a trend where an increase in the bitumen emulsion reduces the stiffness modulus of the samples recorded at 20°C. The stiffness of the samples are reduced when 18% of emulsion is used making it less prone to low temperature cracking at low temperatures. However, to have a sample stiff enough to resist rutting, lower amount of emulsion would be needed, which is also economically beneficial.

Several stiffness modulus values are reported in the literature for two-phases grouted macadams, the only reported value for the material with skeleton produced with cold mix after long-term curing is 3900 MPa found in the research done by Afonso et al. [27]. Considering this value as a reference, it is possible to state that the experimental mixes containing less than 9% of bituminous emulsion can achieve the performance of grouted macadams where the bituminous porous skeleton is cold mixed.

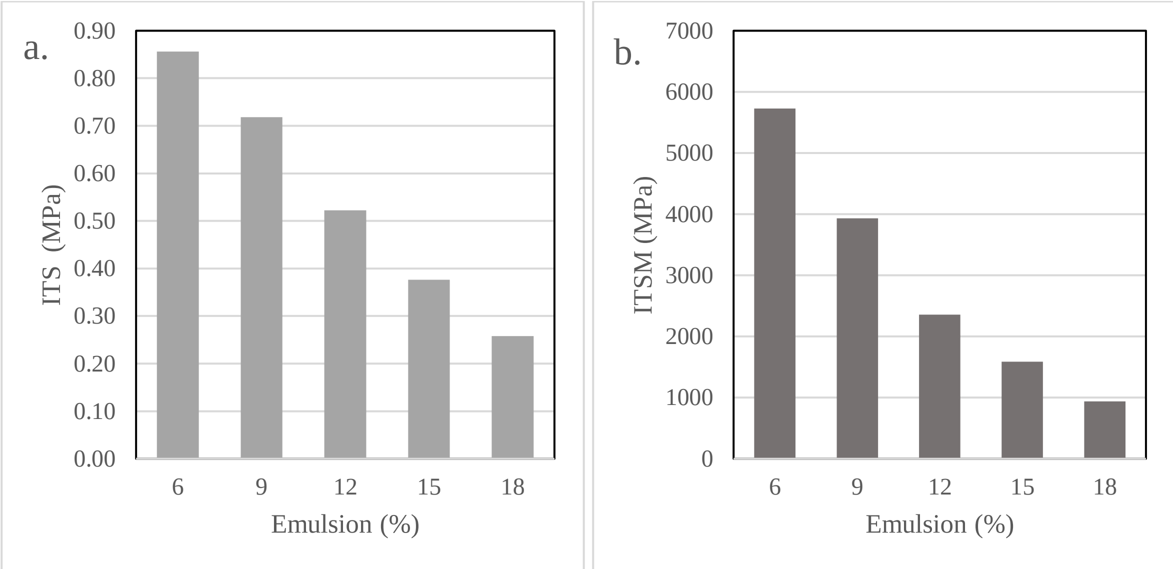

Figure 4. Effect of different bitumen-emulsion percentage on the a. ITS and b. ITSM of bitu-cement specimens

The effect of the cementitious paste content on the final strength of the samples is evident from the results reported in Figure 5 . Samples with higher mechanical performance and stiffness contain higher amounts of cement. The results illustrate that the highest ITS and ITSM values were obtained when 19% of cement was used within the mixture. However, an approximate decrease of 45 and 62% in ITS and ITSM values were respectively recorded when the cement amount was reduced to 8%. The data indicates that a sample produced with lower cement contents would more likely have a less brittle behavior than others.

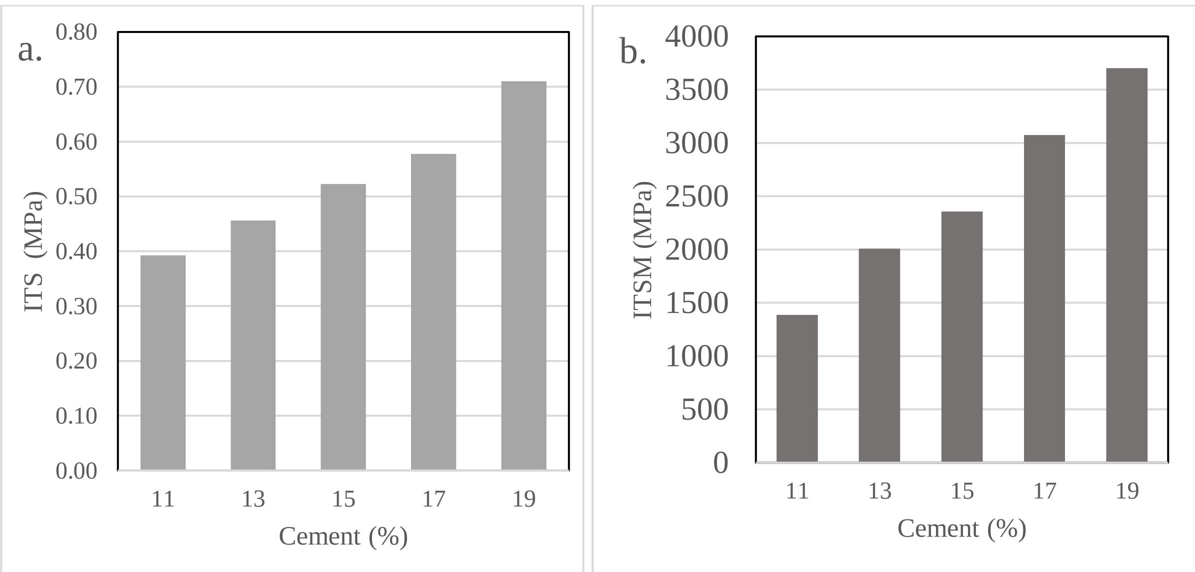

Figure 5. Effect of different cement percentage on the a. ITS and b. ITSM of bitu-cement specimens

The mechanical performance of samples produced with different aggregate percentage is shown in Figure 6. By fixing the ratio of other components, the highest values for ITS and ITSM were observed when 79% of aggregates was used within the bitu-cement skeleton. However, the effect of aggregate on the final performance of the samples was not as dominant as other factors including cement and emulsion contents. Thus, a small decrease of 11% was recorded for ITS values when the amount of aggregates was decreased from 79 to 70%. From the ITS data it could be concluded that higher aggregate volume provided a better packing format of the samples allowing for better densification of the samples. However, a significant trend was not observed for the ITSM values. In fact, regardless of aggregate volume (%), an insignificant difference was observed for the stiffness values. Thus, the aggregate amount did not seem to significantly alter the behavior of the samples against low temperature cracking or rutting distresses.

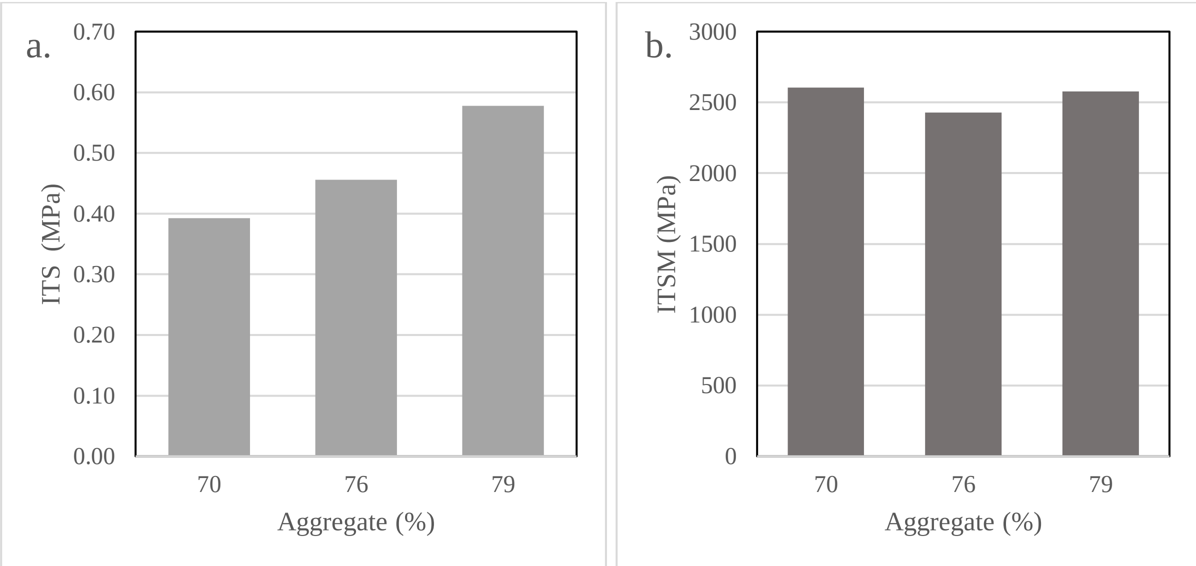

Figure 6. Effect of different aggregates percentage on the a. ITS and b. ITSM of bitu-cement specimens

The optimum water addition to the grouting cement powder for producing the grout slurry is determined 1/3 of cement weight. However, due to water release of emulsion to the mixture during compaction, it is important to evaluate the optimum amount of slurry water needed for the production and compaction of specimens. Samples were produced by only changing the cement to water ratios between 2.5 to 3.5 in cement slurry. The ITS results (Figure 7) did not show significant difference in terms of mechanical strength. So, the effect of minor changes of slurry water in such samples could be neglected. The ITSM results reported in Figure 7 indicated that samples produced with the highest water content had higher stiffness modulus. Thus, by increasing water content to 3.5%, samples will provide more resistance towards rutting.

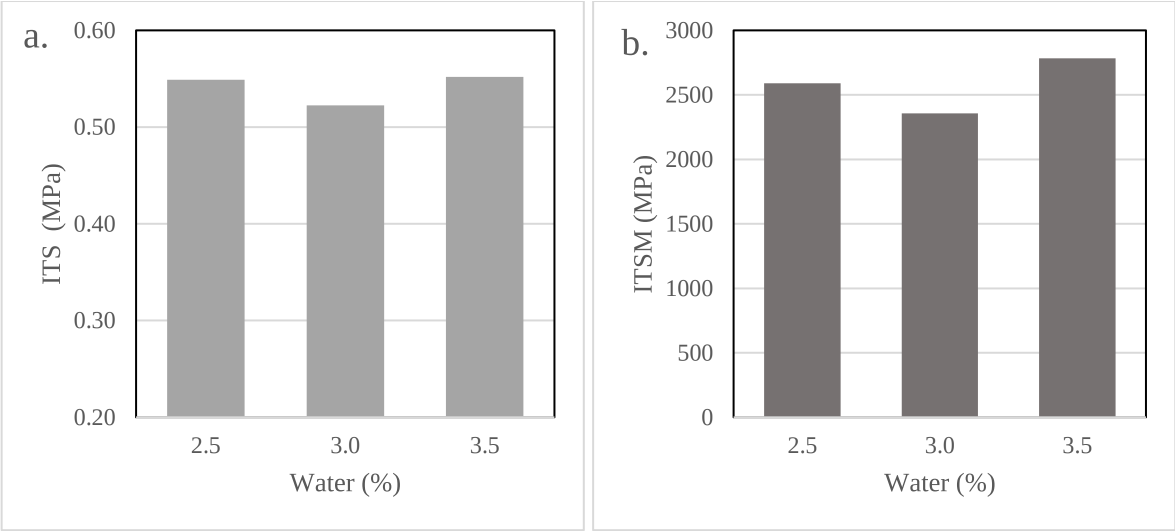

Figure 7. Effect of different cement to water ratios of cement slurry on the a. ITS and b. ITSM of bitu-cement specimens

The overall correlation of ITS and ITSM result values are plotted in the graph of Figure 8. A good linear correlation between the two sets of data was expected for this type of materials. This correlation allows the two-way estimation of values either from one or the other test. It should be noted that the plotted data are obtained from 7-day cured samples. A different correlation would more likely be obtained for different curing times. Considering the fact that in concretes, the increase in elastic modulus usually ends in decrease in final strength due to lower toughness, this coherence of increase between strength and modulus shows that the bitu-cement composite -very similar to semi-flexible asphalt layers- has achieved the idea of having mechanical benefits of both cementitious and bituminous phases (representing solid and flexible pavement layers) without becoming heir to their severe drawbacks.

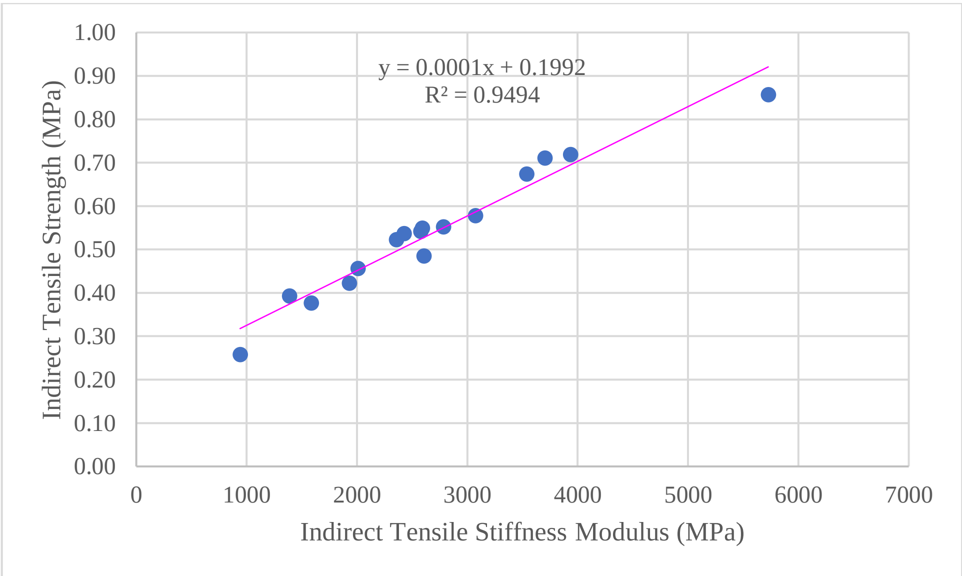

Figure 8. Correlation between ITS and ITSM results of bitu-cement composites (7-day curing).

Ductility

The vertical deformation at failure in ITS tests on 100mm diameter samples can be assumed as an indirect description of flexibility and cracking resistance of the compacted samples. As it is shown in Figure 9, the changing trend of deformation at failure by varying the emulsion and cement percentages, is in full agreement with the recorded mechanical properties. It is clear that by enhancing the stiffness of samples, the ductile deformation of bitu-cement mixes is decreased, which makes the material more brittle and prone to cracking, thus potentially reducing the durability of pavements in cold weather.

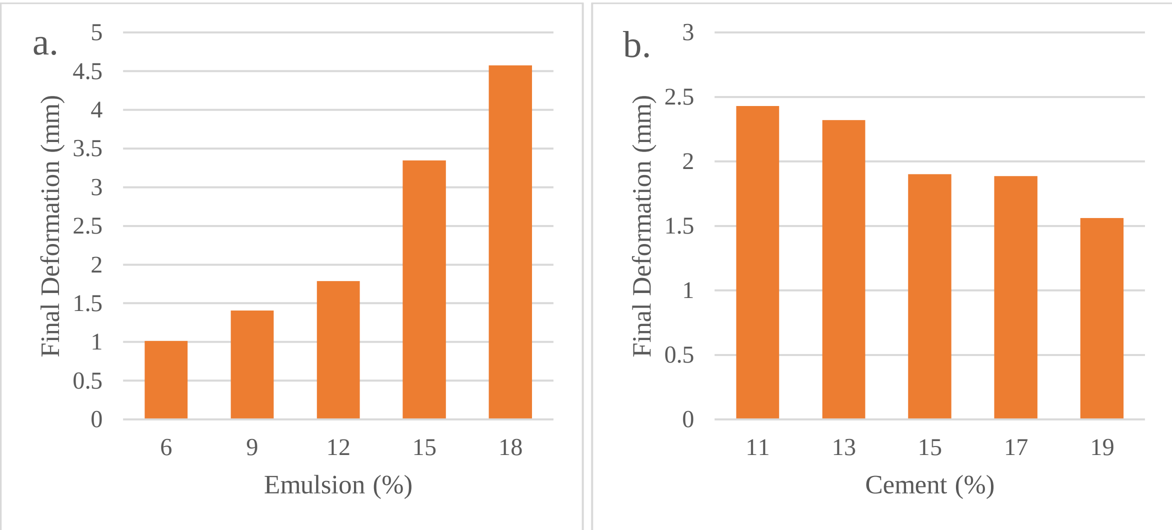

Figure 9. Effect of a. emulsion and b. cement contents on failure vertical deformation of samples in ITS tests.

Loss of water

The water release/loss during the gyratory compaction and the subsequent curing process of the compacted mixes can be correlated with the final properties of the bitu-cement samples. The bituminous emulsion is made of water and bitumen, which releases the excess of water after the breaking during compaction. The presence of free/excessive water/fluid in the loose mix, can consume the energy of compaction to overcome the water release from the material, rather than compacting the mix. Furthermore, the water lost after compaction (i.e. curing), other than acting in the possible cement hydration processes, can also be a source of internal air voids and may hinder the achievement of the targeted mix compaction and density. In Figure 10.a it is shown that adding more emulsion will release more water during compaction, and less changes in water content are recorded during the curing phase. On the contrary, increasing the cement content (Figure 10.b) does not have a clear effect on compaction or on the curing water loss amount.

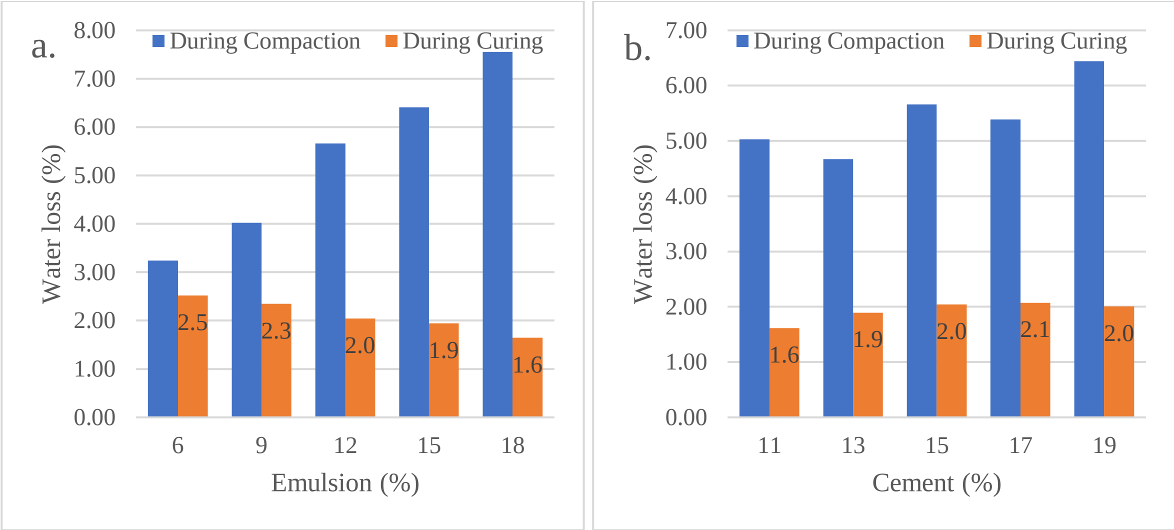

Figure 10. Mass loss due to water release/loss during compaction and curing; a. by increasing emulsion, b. by increasing cement.

In Table 5 , the correlation coefficient of water loss percentage of specimen (in two stages of compaction and curing) with percentage of emulsion-binder and cement powder-cement phase is demonstrated. It shows that emulsion (binder) addition has the highest correlation with water loss of mixture during both compaction and curing, as expected. Therefore, the emulsion content has the highest effect on amount of excess water and void formation in our material.

Table 5. Correlation coefficient of water loss and initial recipe- final constituent components.

R2		Emulsion% (Binder%)	Cement% (cementitious phase%)
Water loss percentage	Compaction	0.72 (0.71)	0.17 (0.11)
	Curing	0.67 (0.66)	0.03 (0.01)

Moreover, understanding the relation of water loss with the formation of void in the structure can give a key insight towards the effect of composition on density and void content. As shown in Figure 11, More water loss in compaction would result in denser structure with lower voids; which could be due to fact that denser structure would be formed if more excess water releases in compaction stage. However, this trend reverses during curing, which water loss increases the void content. In curing, the voids mostly form by absorbing water to cementitious phase. Besides, the evaporation of the water from unsealed samples during curing leaves more voids in the structure.

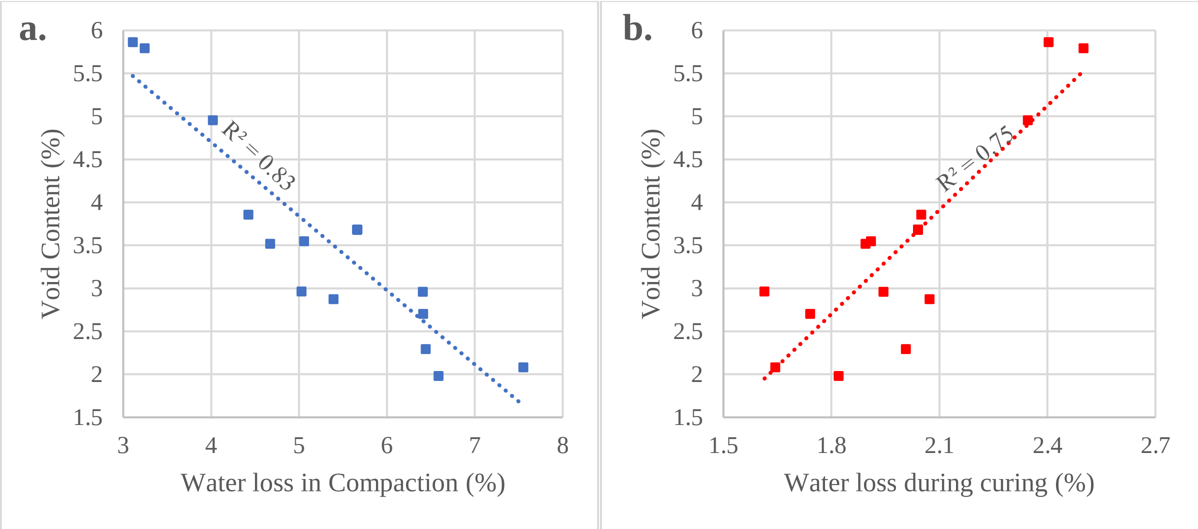

Figure 11. The correlation of water loss percentages and void content percentage, a: in compaction, b: during Curing.

These analysis can be confirmed by evaluating the relation between water loss and ITS result in different groups of samples. As it is shown in Figure 12 a, by changing the emulsion content, the ITS value is obviously related to the amount of water released during compaction: more emulsion releases more water and the excessive residual bitumen can turn the sample to have less cohesion. This trend is also repeated by evaluating the overall ratio of aggregate to binder (bitumen and cement). However, it is shown that variation in ITS values due to cement changes does not have clear relation with the water release during compaction. This could bring to the conclusion that, between emulsion and cementitious slurry, the first one is the main source of water released in the compaction process.

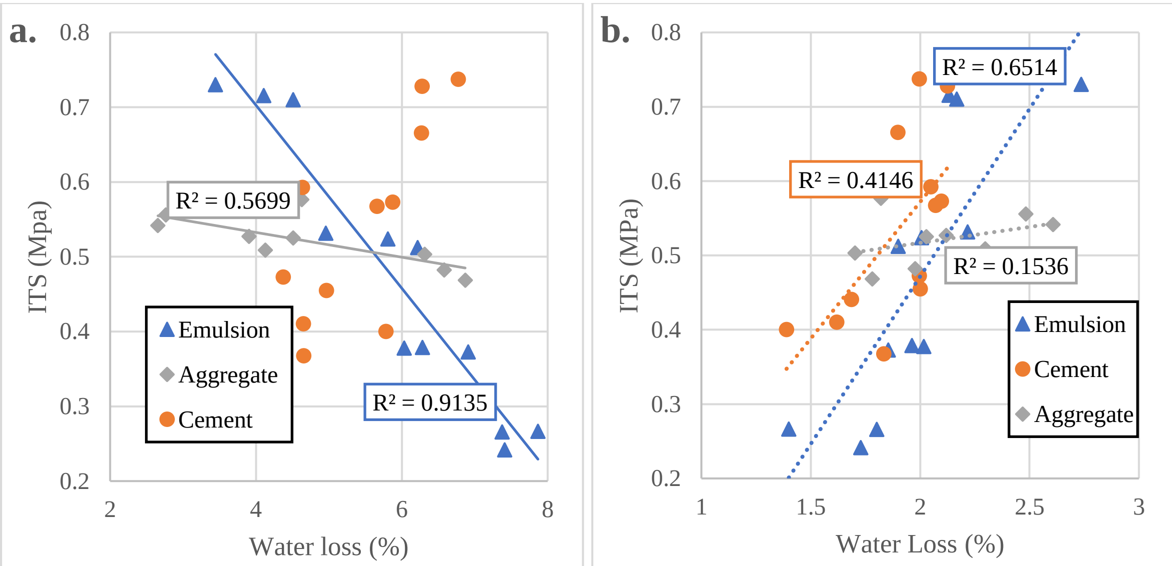

Figure 12. Correlation between ITS and water release/loss during a. compaction b. curing by changing the proportions of emulsion, cement and aggregate.

Figure 12 b plots the relationship of changes in ITS results and water loss during the curing phase by changing proportions of emulsion, cement and aggregates. The positive, but lower correlations compared to those in Figure 12 a are in line with the lower amount of weight loss (corresponding to less than half of the water released in compaction) and with the strength development with curing, due to the hydration processes and hardening of the residual bituminous binder phase.

TRIAL FIELD

Considering the 3900MPa ITSM threshold reported for grouted macadams with cold mixes [27], the mixture with 9% emulsion addition (resulting 5.5% binder) and 15.5% cement (resulting in 17.4% cementitious phase) selected to be used in constructing a single layer pavement for trial field investigation. Two strips were constructed on a stiff gravel subgrade and compacted by roller after grading. Several core samples were extracted from constructed layer and were subjected to densitometry and mechanical tests. The results were shown in Table 6. Comparing to the same composition samples produced in the laboratory having around 2 percent of voids, the core samples have 5 times more void content. This means much less compression of the mixture in the field comparing to the laboratory compaction. However, the mechanical properties are maintained despite higher porosity.

Table 6. Averages of results of the tests performed on core samples, and the statistical coefficient of variation.

Bulk density (Mg/m3)	**1.928** (CV=2.44%)
Void content (%)	**9.987**
ITS (MPa)	**0.60** (CV=23.0%)
Final deformation (mm)	**0.93** (CV=32.17%)
ITSM (MPa)	**4507** (CV=18.84%)

CONCLUSIONS:

This research paper promoted the feasibility of 100% RAP recycling in a semi-flexible pavement by production method of cold direct mixing. The research successfully reduced the two-stage construction process of traditional grouted macadams to a single stage of mixing, like it is for most of the common bituminous materials. A cold mix emulsion was mixed with cement slurry to produce the final product containing full RAP instead of virgin aggregates. The up scaling of this approach would be very beneficial for the industry since it will allow the use of 100% RAP recycling in cold semi-flexible pavements. However, this would not be possible through Hot mix or Warm mix methodologies since it would be impractical to provide a RAP grading that would at least provide 25% air void content.

The following conclusions could be drawn for the current study:

- The goal of obtaining similar mechanical results was met by proportioning the RAP aggregates into a 50-50% batch containing fine and coarse sized bituminous material.
- The mixing procedure plays an important role in the final performance of the mixture. Samples were fully coated by cement slurry when the emulsion was added in the final stage of the mixing process.

- Aggregate volume and slurry water percent seem to have the least effect on the strength and stiffness of the bitu-cement samples.

- Increasing the bituminous binder portion by addition of emulsion to the mix, causes continuous decreasing of the void content, however the effect of cementitious phase portion on void content is not linear, as there is a peak in void percent in 17% cementitious phase.

- Higher cement content increased the final strength of the samples in terms of indirect tensile strength and indirect tensile stiffness modulus. It will produce mixtures that would be more susceptible to brittle cracking compared to those with lower cement content.

- A very consistent correlation can be drawn between ITS and ITSM values for the samples produced and cured for 7 days.

- An increased amount of cold-mix emulsion resulted in lower stiffness of the sample. This was due to the visco-elastic nature of bitumen mixtures and its emulsions. Thus, samples produced with the lowest amount of emulsion had the highest strength and stiffness.

- The mixture void content and degree of compaction in the field layer are higher and less than laboratory compaction, relatively; however, the mechanical properties are maintained.

- Water release during compaction of the mix is one of the main consequences of the compaction process, which is mainly related to the amount of cold mix emulsion introduced in the mix. The lower ITS values are related to the quantity of bitumen; hence a negative trend is expected also for the corresponding loss of water.

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Appendix: Additional pictures related to chapter 5

Left: The bitu-cement mix before compaction. Middle: The specimen of the reference mixture. Right: Series of compacted specimen during 7days curing.

Construction of trial field layer.

Core Samples cut from the layers.

CHAPTER 6: CASE STUDY: A GEOSYNTHETICS-AGGREGATES SANDWICH REINFORCING SOLUTION FOR IMPROVED BEARING CAPACITY OF FARMING PADDOCKS

FOREWORD

Surface soil stabilization and geosynthetics reinforcing methods used in pavement engineering for improving the bearing capacity of layers, can be also potentially implemented in various farming areas. The main scope can be trafficability of impervious areas, but also the walkability of paddocks and other similar foraging areas for husbandries, while extending their seasonal use to more wet periods of the year. Several types of ground improvement techniques involving stabilizing or reinforcing of clayey soils are available for these types of applications. In this case study one of the most common geotechnical anti-erosive and reinforcing method for pavements and slopes, geocells, are applied to an outdoor paddock for the cattle of a bio-farm. This chapter presents the experimental site set up to evaluate the feasibility and performance of a low-depth sandwich layer made of two geosynthetics and a 15 cm thick geocell filled with natural aggregates, used to improve the drainability and bearing capacity of the superficial clayey soil. The test area was located inside a real husbandry paddock to validate the potential improvement of the 3D proposed reinforcement solution. It was decided to create a demo area and test its performance versus a control zone without reinforcement. The results obtained from data recorded in different periods of the year, were very promising due to the moisture controlling properties of the implemented system, which avoids the mud formation of clay in wet seasons and drying shrinkage in dry seasons.

Case study: using a geocells-aggregates sandwich layer to improve load-bearing and drainage properties of farming paddocks

Abstract. Reinforcing the weak surface soils of farming paddocks can improve the effectiveness of their use for the health quality of livestock and extend their seasonal use. Many geotechnical methods can be utilized for this scope, but coupling the use of underground geocells, drainage geosynthetics and simple gravel can be one of the novel interdisciplinary implementations of engineering reinforcing solutions in the husbandry industry. Animal walkability, controlled soil surface humidity, and improved grass coverage of the paddock could be easily improved by the application of the above-mentioned sandwich system. In this study, the effect of a geosynthetic-geocell-aggregates sandwich reinforcing system applied below the surface clayey soil of a husbandry paddock is investigated by measuring the humidity, bearing capacity, settlement and visual roughness in two testbed zones compared to adjacent untreated test areas. It is shown that moisture control of the clayey soil in the reinforced areas is one of the main factors governing the bearing capacity and surface texture of the paddocks in different seasons.

INTRODUCTION

The growing need for the increase of efficiency/walkability/drivability of many unpaved areas in the farming sector such as rural roads, farm passages, pens, feedlots and animal paddocks are linked to the improvement of the load bearing and drainage quality of natural existing or excavated soils in these areas. One of the possible methods for improving the outdoor areas such as enclosed pastures or paddocks is installing geosynthetics or bio-mats materials in soils. Geotextiles (either synthetic or bio-based) are usually permeable fabric materials used in engineering applications. Despite being utilized mostly to separate, reinforce, filter or drain, geotextiles are sometimes coupled or joint to provide a composite system that can be used as waterproofing membrane. Various types of geosynthetic materials are used today to tackle the different challenges of civil engineering applications, above all soil reinforcement and slopes stabilization. They include geogrids, geotextiles, geomembranes, geonets, geosynthetic clay liners (GCL), geocells and geo-composites, which are mainly made from polypropylene, polyester, polyethylene, polyamide or other polymers and glass [1,2]. Geocells are often used to preserve embankment and cut slopes of roads and other transportation infrastructures, but can be also used as structural/drainage layers to provide bearing capacity and drainage ability to the upper paving structure. Many researches have been done in laboratories to evaluate the effect of utilizing geocells in improving loadbearing properties and strength enhancement of subgrade soils [3–9] together with in field case studies. As a dominant example, Cristelo et al. clearly demonstrated that under confining pressure, friction angle and cohesion intercept of the soils for reinforced by geotextile increase by the order of 8% and 13% respectively [10], which shows the necessity of utilizing these reinforcing systems in weak strength envelops of soils under sensitive functions.

The scope of the proposed research case study is the assessment of the feasibility of improving the overall walkability and drainage conditions of a real animal paddock and possibly extend its seasonal use into the wet periods of the year. The improvement should not correspond to the use of surfacing materials or chemical or geometrical (adding gravel) stabilization treatments, nor to the removal of the existing clayey soil that should be kept in place for the development of grass coverage.

RESEARCH METHODS

Trial field design and construction:

Two rectangular areas of 2.5 meters width and 8 meters length were selected for implementing a reinforcing sandwich layer made of geo-cells, gravel, woven geotextiles and non-woven geo-mats, in an enclosed paddock of a cow husbandry containing up to 500 Holstein milking cattle, each of them weighing on average 700 kgs. The paddock is used for walking and feeding the cows in certain hours of the day, in order to achieve the standards of biologic food product for their milk.

Figure 1. Top view of the paddock and the plan and dimensions of considered zones (fields) for implementing geocells, plus adjacent test areas.

As shown in Figure 1, one of the areas was located at the entrance of the paddock, assuring that all the cows pass over it, while the other one was located far from the entrance, in a portion of paddock that is normally used by animals to lay and rest. The considered areas were first dug down to the average depth of 15cm from the existing surface to implement the reinforcement using HDPE geocells with the height of 10cm; the designed solution considered additional 5cm of top soil. A layer of separation geosynthetic was laid over the bottom soil of the treated areas, following by fully stretched lightweight HDPE carbon stabilized geo-cells filled with natural pea-gravel (Figure 2).

Figure 2. The steps of implementing geosynthetics and geo-cells. a. removing top soil, b. laying geo-synthetic, c. stretching geo-cells, d. filling with gravel, e. sandwich closure with geo-synthetic and positioning of natural top soil

A second permeable layer of geo-synthetic non-woven mat was laid on the top of the gravel-filled geocells, and the area were covered with soil over the geocells sandwich. The producer declared characteristics of the geo-mat layer are shown in Table 1.

Table 1. Properties of the geo-mat.

Nominal weight per unit of area	EN ISO 9864	$200\ g/m^2$	
Width	2m		
Tensile Strength	EN ISO 10319	MD	2 - 0.6 KN/m
		CMD	2 - 0.6 KN/m
Elongation	EN ISO 10319	MD	55 ± 20 %
		CMD	65 ± 20 %
Static puncture resistance	EN ISO 12236	300 (-100) N	
Pyramidal puncture resistance	EN ISO 14574	NPD	
Dynamic Perforation Test	EN ISO 13433	>50 mm	
Characteristic Opening Size	EN ISO 12956	80 ± 30 μm	
Permeability normal to the plane	EN ISO 11058	0.098	

TESTING METHODS AND SCHEDULED MONITORING:

In order to characterize the bearing capacity of the existing materials and of the proposed solution a number of traditional bearing capacity tests was performed on the subgrade excavated surface, on the untreated soil surface and on the completed reinforced top soil. Water content was also assessed in the treated and untreated areas after the winter season.

A series of Light Weight Deflectometry (LWD) and dynamic portable California Bearing Ratio (CBR) tests were done over the subgrade surface, before laying the reinforcement, and on the top soil surface after levelling it with soil. Some days after construction and before letting the cows walk over the paddock terrain, a photogrammetry surveying campaign was done by means of an instrumented light drone. The surveying geomatic acquisition was repeated in autumn after 152 days from the first survey, in order to measure possible changes in the geometry of the terrain.

Moreover, after 32 weeks (225 days) during which the paddock was regularly used by animals in the winter season, another series of LWD, humidity measurements and sampling were done over the trial areas. Measurements were done inside and outside of the reinforced areas, for comparing the reinforced area with an untouched control area.

Drone photogrammetry was performed in two times: first, some days after implementation of the geocell system before the start of animals grazing in the paddock; and second, after several months of animal grazing and walking over the reinforced areas during wet winter season. The photogrammetry operations were done to gather and compare the information about the elevation level and terrain quality before and after the implementation of geocells sandwich layer.

RESULTS AND DISCUSSION

The testing results obtained from the initial LWD and dynamic CBR measurements of the subgrade soil surface of the area during construction on 14th of July 2021 are shown in Table 2.

Table 2. Results of the spot tests in the day of construction.

	point	**CBR**	**LWD**	**CBR average**	**CV%**	**LWD average**	**CV%**
Field 1	Bottom-1	33	27.3	38.5	23.7%	29.775	27.3%
	Bottom-2	52	30.5				
	Bottom-3	36	40.4				
	Bottom-4	33	20.9				
	out1	-	43.2	-		31	55.7%
	out2	-	18.8				
Field 2	Bottom-1	87	37.1	77	14.8%	33.46	22.2%
	Bottom-2	77	43.8				
	Bottom-3	61	32.3				
	Bottom-4	83	24.2				
	4bis	-	29.9	-	-		
	out1	-	24	-		32.425	27.2%
	out2	-	41				
	out3	-	39				
	out4	-	25.7				
Gravel	1		10.5	-		10.5	0%
	2		10.5				

It is shown that the average bearing capacity and coefficient of variation of the two dug areas are very similar to those of the soils outside the areas (non-treated zones). This shows the consistency of the existing soil down to the depth of 15cm. Values are lower than those of common embankment layers and are in line with those of a superficial dry natural clayey soil.

Along with LWD, the dynamic CBR test was adopted to assess the bearing capacity of the sandwich reinforcement bed soil. The test, like the laboratory one, records the resistance to penetration of a cylindrical piston hammered on the soil with the same LWD falling weight system. Dynamic CBR is considered to be more accurate in soft soils than stiff ones [11], but it can be affected by the presence of large gravel particles underneath the piston. Despite the similarity with LWD results from the subgrade soil of the two reinforced areas, the CBR results shows higher differences.

The result of LWD tests performed over the gravel filling of the geocells reinforcement indicates that the sandwich does not actually provide higher stiffness, but it contributes to the surface homogeneity by means of a damping effect that is actually reflected in the LWD behaviour on the gravel. The LWD shows very low values due to the elastic deformation of the sandwich layer subject to the plate impulse.

The humidity results obtained from the testing campaign of March the 1st, 2022 in the experimental zones are shown in Table 3. The samples were taken from an average depth 10cm. Low variation of the humidity content, also reflected by the coefficient of variation, indicates that there is homogeneity in the distribution of water content in the zones, and confirms that on the reinforced sections surface water ponds did not form, but the soil humidity was kept. The soil type of the paddock was clay, which generally have high moisture content after the wet season to favour the growth of grass in spring.

Table 3. Humidity of paddock soil in different points.

		Average humidity	Coefficient of variation (CV)
Field 1	Inside	34.18%	5.28%
	Outside	27.38%	2.24%
Field 2	Inside	22.85%	1.31%
	Outside	18.70%	3.73%

Taking into account that the surface mat of the zones was much more permeable than the geotextile which is placed under the zones, higher and better drainage of the test zones was expected. But by measuring the humidity of soil samples (Table 3) it is clear that the depth of cover soil and filled gravel of geocells, do not provide such excellent drainage that it can be experienced by humidity measurements. This, together with considering the impermeability of bottom geo-synthetics, gives the conclusion that the draining properties is not necessarily improved by the implemented geocell system. Complementary research is needed to investigate the drainage parameters in the embedded reinforcing system, studying the depth, thickness, filling and the top soil type effect on the draining properties of the experimental and control areas. From the visual observations done in the middle of the wet season (second half of December 2021 - Figure 3) it was seen that the reinforced fields drain more water than the adjacent control areas, where some small pits filled with water can been actually seen.

Figure 3. The test areas in middle of the wet season. Left: Field 1, Right: Field 2.

In Figure 4, the visual characteristics of the surface of the inside and outside soil of the two experimental zones after the end of the wet season (Spring 2022) are shown. Photos a and c are related to the top soil of fields and b and d are related to the unreinforced soil parts of the test areas. It is evident that there is a remarkable difference in appearance of the various areas. The unreinforced control areas are clearly more rough and show the typical signs of shrinkage due to drying of wet clayey soils. On the contrary, the natural soil on the treated areas seems to be more homogeneous without suffering suction mechanisms causing cracks. This can be due to the presence of the sandwich layer under the top soil, which can allow the drainage of the pavement and hinder the formation of shallow ponds eventually leading to suction effects in the dry period. An alternative approach is to consider the possible water storage effect of the sandwich due to the lower permeability of the bottom geomat that may help to keep the humidity of the top soil due to the capillary effect. This could be also in agreement with the laboratory humidity results of soil samples, which exhibit higher humidity in field top soils.

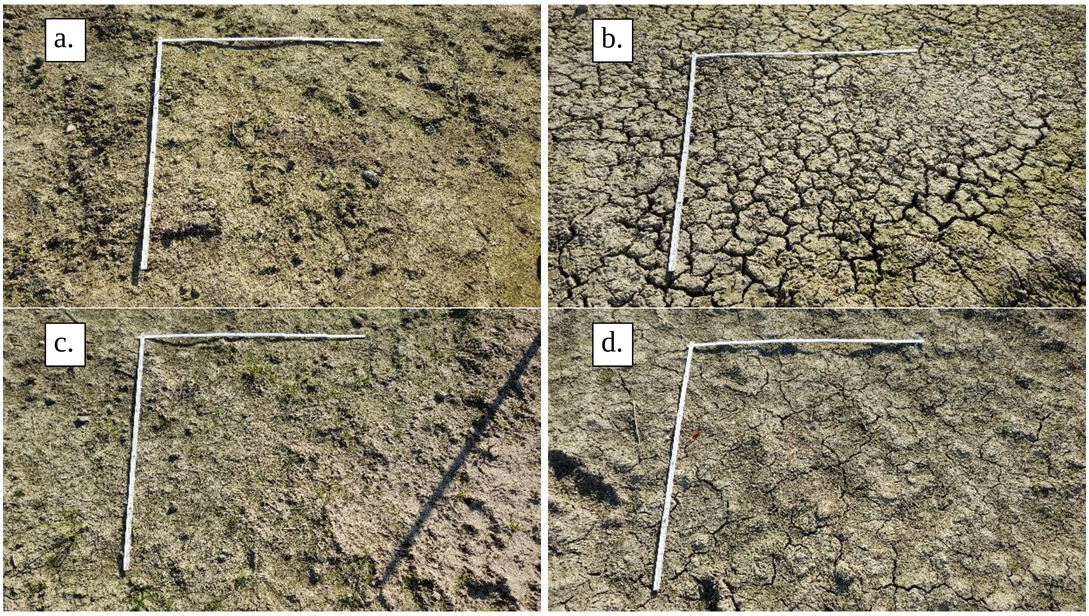

Figure 4. Differences in the visual characteristics of soils after the wet season. a. inside zone 1, b. outside zone 1, c. inside zone 2 and d. outside zone 2.

The behaviour of system can be interpreted as a consequence of the draining properties of the sandwich during time. It appears that, at the beginning of the wet season, the implemented sandwich system improves the draining and water absorption of the area, which prevents the formation of mud and water pits in the clayey topsoil that decreases the efficiency of paddock to be used by cattle. However, it seems that the sandwich geocell system can contribute in keeping the humidity of the topsoil in the dry season, which hinders the drying shrinkage (suction) in the clay soils and helps the growth of grass. This could be very useful in extending the high-efficiency period of paddocks in the dry climates, which have abundant amount of rainfall in wet season, but low participation in the dry seasons.

The LWD tests' results obtained in Spring 2022, after 225 days of implementation of the reinforcements in the field are shown in Table 4.

Table 4. LWD results after 225 days from sandwich system implementation.

		point	**LWD (MN/m^2)**	**Average (MN/m2)**	**CV (%)**
Zone 1	Inside	(1)	(0.9)	5.7	10.3%
		2	6.1		
		3	5		
		4	5.9		
	Outside (control)	5	19.3	15.2	27.2%
		6	18.1		
		7	11.6		
		8	11.6		
Zone 2	Inside	(1)	(16.8)	6.27	14.5%
		2	7.1		
		3	6.4		
		4	5.3		
	Outside (control)	1	6.8	8.58	14.8%
		2	9.6		
		3	8.3		
		4	8.2		
		5	10		

Both experimental zones present have lower bearing capacity than the control areas, where the deviation in out area of zone 2 is higher than the inside. All values are very low if compared to common pavement foundation layers and to the previous test results obtained from the subgrade existing soils before the wet season (during the summer construction). The values inside the treated areas are slightly lower than those obtained on the filled gravel layer during construction and this is more likely to be attributed to the humid topsoil. On the contrary, the control areas are stiffer than the treated areas, but their surface appears much more cracked. This will lead to rough and stiff surfaces as the dry season evolves, while the damping effect of the sandwich system will keep the surface less stiff and more even.

Based on the above, it should be considered that the efficiency of the geocells system should be assessed not only immediately after its implementation, but in a longer term, in order to let settlements to act under the loading of animals and water ingress. Besides, the higher CVs of zone 1 outside data for both humidity and load bearing capacity (LWD) indicates that despite the untouched area has higher LWD values, it has less homogeneity comparing to the inside area. So, improving the uniformity of humidity and load bearing capacity can also be added to the advantages achieved by implementing geocell sandwich systems in paddocks.

SURVEYING

Elevation

The elevation difference based on the drone orthophotos and digital model of train is displayed in Figure 4. No considerable changes in elevation can be measured. The average results of elevation measuring are shown in Table 5. All the reinforced and control zones were slightly uplifted, which is higher in zone 1.

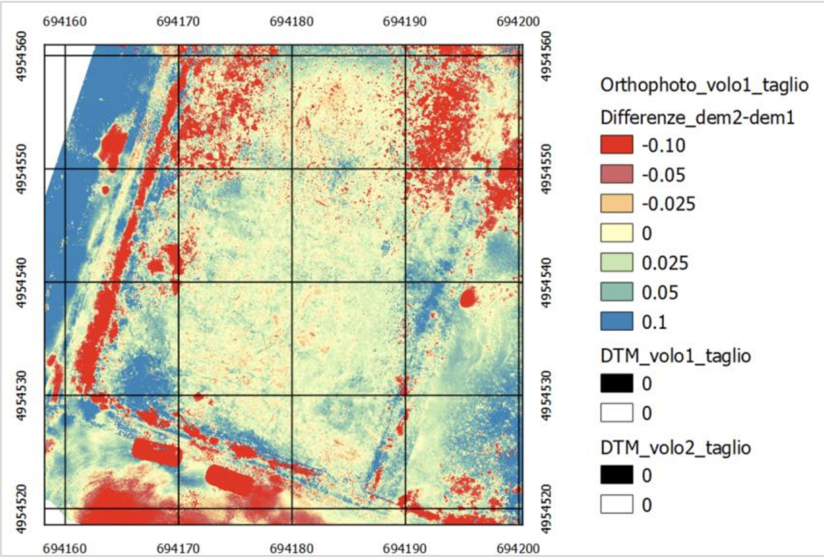

Figure 4. Elevation difference before and after wet season.

The lack of significant changes in elevation of both reinforced and control zones shows that in general the settlement due to the weight load of animals on their hoof is not enough for causing any significant plastic deformation in the topsoil layer of paddock area. However, the change in zone 1 is more sensible, as the number of the animals passing over the entrance area is much more than other zones.

Table 5. Average measured elevation of strengthened and control zones.

Zone		**Average Elevation (dm)**		
		1st survey	**2nd survey**	**Difference**
1	Inside	10.4649	10.4807	**0.016**
	control	10.4016	10.4253	**0.024**
2	Inside	10.4442	10.4481	**0.004**
	control	10.4025	10.4127	**0.010**

Roughness

Despite the fact that the changes in elevation before and after wet season were neglectable, the elastic mud formed after wet season precipitations is expected to affect the surface smoothness of the paddocks.

Visually, animal footprints and the effects of water stagnation are very well observed in control areas. The roughness of the test and control areas before and after the wet season were measured using orthophotos and digital model roughness tools of TRI and QGIS of the terrain, as shown in Table 6. It is evident that despite the fact that the changes are very small, the roughness of the most zones increase during using the paddock by cows in wet season. However, the only expectation is related to the reinforced area of zone 2, which it looks like the geocell sandwich implementation decreased the level of roughness in respect to before operation state.

Table 6. Average measured roughness indices of strengthened and control zones.

Zone		**Average roughness**		
		1st survey	**2nd survey**	**Difference**
1	Inside	0.010961322	0.025660759	0.01469
	control	0.009415949	0.021271508	0.01185
2	Inside	0.010557001	0.009554209	-0.001002792
	control	0.00848972	0.009490743	0.001001023

CONCLUSIONS

Despite the presented results are preliminary, the implementation of the geocells, gravel and geotextile sandwich system has given undeniable benefits to the applied natural surfaces, such as improving the walkability of the paddock soils in different seasons. However, by optimization of the depth, filling material and geotextiles type with reference to the existing soil type, weather conditions and animal hoof load, many other advantages like better drainage and improved load bearing capacity can be added to the list. There is clearly a different behaviour of the sandwich system in depending on the season: in the wet seasons, geocell sandwich help the drainage of the soil and prevents decreasing the terrain quality of paddock soil due to the formation of mud and puddles. While, the system could regulate the humidity of the topsoils and prevent drying shrinkage (suction) in clayey soils during the dry seasons, which can hinder the formation of an irregular stiff surface due to cracks and loss of humidity. At the same time, the damping effect of the sandwich system can provide a better/safer walking surface for the animals. This aspect will have to be assessed in future work. The described dual effect can be very helpful in places characterized by wet and dry seasons. The photogrammetry surveying shows very minor neglectable changes in elevation and roughness by utilizing geocell system, which provides the benefit of feeling the soil completely natural by animals, despite the draining improvements.

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CHAPTER 7: CONCLUSIONS AND RECOMMENDATIONS

The main aim of this multi-purpose research was to provide novel knowledge and practical know-how for the extended applicability of fully recycled mixtures of aggregates and green/durable construction solutions to rural roads and farming pavements.

In many construction projects, especially those located in emerging countries, large amounts of natural materials are utilized just for developing the rural and low traffic road network. Hence, in a climate changing scenario with lack of resources and abundance of wastes, the issue of depletion of natural materials is being tackled from a wide number of researches. The here presented research falls within this context and targets the introduction of a more sustainable alternative for traditional virgin aggregates and materials, in the construction of low-traffic rural roads and all those potential applications of farming pavements where traditional solutions are today still used. The comprehensive research work has foreseen a series of laboratory tests and two main case studies in as many full-scale monitored trial sites. The adoption of thresholds from existing specifications referred to traditional materials and their application to the selected sustainable aggregates and solutions was proposed in order to make a direct comparison of the new approaches with the existing ones. This was particularly true when the chemical constituents and polluting potential was assessed in the laboratory to verify that the novel solutions were not detrimental for the environment, especially in agricultural contexts.

This chapter summarizes the main findings from the completed research on the application of the selected alternative sustainable materials and solutions in rural and low-traffic roads and other minor pavements in farming facilities. In addition, some relevant recommendations for future research work are also provided to the reader.

CONCLUSIONS

The importance of replacing the virgin natural aggregates with more sustainable solutions, highlighted the studies on one of the major solid wastes increasingly generated all over the world that is waste from construction and demolition (CDW) activities on infrastructures and structures, which can also be generally presented as wastes from civil engineering activities.

So far, CDW aggregates have been widely adopted for road pavements. This means that the studies and case histories related to the use of these aggregates in road layers are abundant; however, only few researches focused on the performance of these materials in low-traffic roads and farming pavements. Indeed, the vast and distributed nature of rural and low-traffic pavements demands promising and affordable solutions that should make use of the available materials and allow an easy maintenance, including the re-recycling approach. This means that, the suitability of the recycled aggregates for those pavements should be studied in a more specific way, as it will have direct effect on durability and quality of these fundamental connecting infrastructures, also considering the fact that the rehabilitation and maintenance of these roads and pavements are often of minor concern for road authorities and farmers.

In chapter 2, the main outcomes and findings of the previously performed researches on applications of recycled aggregates in pavements are reported, and the background of various recycled materials employed for different road layers was described through a broad literature review. These researches are mainly performed at the laboratory scale; however, some full-scale case studies have been also considered due to their similarity with the main aim of this thesis. Understanding the properties of each types of recycled aggregates and how it influences the blend performance has provided a general overview of possible aggregate combinations. Besides that, a fair amount of studies has been found on compacted unbound layers. The identified outcomes, limitations and recommendations proposed by other studies on recycled aggregates' applications have been taken as a benchmark for this research. In the literature, it is demonstrated that recycled aggregates can be successfully employed for pavement layers, and their test methods, production, laying, grading etc. are completely similar to traditional aggregates. Compared to traditional natural or crushed aggregates, it is shown that the recycled aggregates can perform as good as natural aggregates and even due to some residual binding activities in crushed concrete aggregates, their stiffness can increase in time.

In all case studies, it is shown that a single or double layer of well compacted recycled aggregates would have sufficient performance to be used in low-traffic pavements, showing the possibility of constructing simple pavements for rural areas and farming facilities using these aggregates.

The second part of chapter 2 is devoted to researches related to recycling the agriculture residue waste for pavement applications. These wastes are mainly generated in large amounts in agro-societies of developing countries, unlike the aggregates originated from construction and demolition wastes, which are more abundant in developed countries. It is clearly demonstrated that the various recycled products from these bio-wastes can be successfully employed in pavements for soil stabilization and reinforcement. This would have important benefits in countries where soft clayey soils are common, such as India, Nigeria and other central Africa ones. Due to their low bearing capacity and high moisture dependency, treating these soils before laying and compaction is a fundamental step that sometimes becomes very challenging due to the scarcity of additive materials and machinery. The agriculture recycled waste can be utilized in various forms in pavement layers, including unbound, hydraulically-bound, hot and cold bituminous mixes. In many studies, they have recognized effects in improving the properties of the existing and newly constructed layers. Not only directly adding them to soils and mixes, these recycled materials can also contribute to improving the properties of bituminous binders.

This can open a new perspective of using these materials not only in rural paving materials, but also in bituminous pavements of major roads.

In chapter 3, the laboratory investigations are mainly focused on the mechanical properties of the recycled materials, including their fragmentation and compaction behaviour; however, the chemical and environmental effects of using these materials on water, soils and farm ecosystems were assessed by means of chemical composition and leaching tests. It was clearly shown that in recycled aggregates, the change in grading curve due to the breaking under mechanical loads is one of the main mechanisms effecting the stiffness gain during compaction. Nevertheless, due to the fact that the nature of these aggregates is consisted of several constituents, the result of their compaction differs from strong virgin natural aggregates. It is shown that the cement mortar attached to natural aggregates in CDW blends has less resistance to fragmentation than the very same aggregates, which leads to high fragmentation values. As a result, the compacted material is made of two main phases: coarse hard natural aggregates and fine powder from mortars. Moreover, the possible stiffening effect of residual cement in CDW aggregates can influence the time-dependent load bearing capacity of unbound and cement-bound layers. Finally, the results of horizontal Dynamic Surface Leaching Tests (DSLT) revealed that the release of hazardous substances including heavy metals and trace elements from all these aggregates were far below the EU Water Framework Directive limits and their possible application in road construction was safe, which proves the suitability of these aggregates for farm roads.

In the first part of **chapter 4,** the stiffness development of selected blends of aggregates was evaluated by means of continuous control roller compaction on a real road trial-section as main case study of the research. Stiffness graphs were recorded by smart vibrating rollers equipped to perform Continuous Compaction Control (CCC) assessments over the lanes made of various aggregates. The weaker sections were those made of materials with lower resistance to fragmentation, such as bricks, elongated tiles and masonry particles; However, the grading distribution of the unbound mixes can help into reaching the maximum stiffnesses as compaction proceeds. It is shown that the behaviour of mixes containing bituminous aggregates is different from others due to visco-elastic nature of RAP. The stiffness development evolves with similar trends in layers mainly containing cementitious aggregates, which exhibited a higher and uniform stiffness that overlapped the non-uniform subgrade. Thanks to CCC measurements, it was proven that there is an optimal number of passes for each material and applying more roller passes does not improve the stiffness, while it can be detrimental.

In the second part, numerous spot tests were performed to correlate their results with CCC graphs, and identify some possible quality control limits in line with existing literature and requirements. It was found that, the time-dependent stiffness development of recycled concrete aggregates sections has a relevant effect in the correlation of roller compaction stiffness data with spot test results. Moreover, the rate of stiffness gain of sections made of different materials depends on their constituents, and the roller measuring depth is a key variable when it comes to define correlations and limits for different layers. Overall, it is evident that different blends of recycled aggregates need different number of roller compaction passes to meet the thresholds defined for spot tests. These measurements should be considered in each pavement construction operation by recycled aggregates. In terms of durability of the proposed materials, the trial road exhibited excellent performance under heavy traffic during winter, which proves their aptness for the use in single layered unbound pavements exposed to harsh weather.

In chapter 5, an innovative method for the construction of the surfacing layer of rural roads and special farming pavements is presented. A sustainable alternative to traditional semi-flexible pavements (mainly known as grouted macadams) is proposed that makes use of RAP aggregates only. In this approach, cement grout slurry is directly added to RAP aggregates before mixing with bituminous emulsion, to form a dense composite with a two-phase binder. By assuming an initial porosity of 25% as an average value for the bituminous skeleton of common porous asphalts for semi-flexible layers, the amount of added cementitious slurry is calculated and the volumetric composition is optimized by measuring the mechanical properties of samples produced by varying the proportions of constituents of the composite mix. It is proven that, increasing the percent of cement will improve the stiffness and mechanical properties of the material, which is reflected in ITSM and ITS mechanical results. However, the toughness of the samples will decrease by adding the cementitious phase, which makes the material more brittle. This brittleness can be a source of cracks in real pavement surfacing, which is usually to be avoided. Besides, the released excess water during compaction and aging of the proposed cold mix should be considered as it can despoil the energy of roller compactors and hinder the mix to achieve its maximum stiffness and bearing capacity. It is shown also that increasing the quantity of emulsion the value of weight reduction due to water loss increases, and by increasing the ductile binder phase, the stiffness decreases. Overall, the proposed semi-flexible layer could be successfully adopted in low traffic layers, however further optimization is needed based on the application and service conditions.

Finally, in the last chapter **(chapter 6)**, a common technique of geotechnical engineering is applied to a bio-farming paddock devoted to the external activities of cattle husbandries. Geocells and geo-synthetics are widely used in subgrade and foundation stabilization and reinforcement of roads and pavements built on soft soils and on weak slopes. The main aim of this implementation was to improve the bearing capacity and drainability of the existing paddock clayey soil and improve the quality of mobility and grazing of heavy livestock over a clayey muddy paddock, especially during the wet seasons. The implemented sandwich system is consisted of a permeable layer of geosynthetic over the bed soil of a 15cm dug area, a 3D geocell system laid over the geosynthetic and filled with gravel, and a second permeable geosynthetic laid over them, followed by the existing top soil. Despite the fact that the implemented sandwich system does not provide any improvement in bearing capacity measured by LWD spot tests, it improves the humidity condition of the soil by favouring the water drainage. It is clearly demonstrated that the implemented system prevents the formation of mud during the wet seasons; also, in dry summer it hinders the cracking of the clayey soil due to drying shrinkage. This moisture regulating function of the geocell sandwich can be highly useful in many regions where the annual precipitations are cumulated in few months of the year. This will have a considerable improvement in the overall condition of the paddocks for cattle and other natural surfaces devoted to animals' activities.

Overall, this thesis has clearly demonstrated the feasibility of using the selected sustainable recycled aggregates for low-traffic rural roads and the pavements used in farm and agriculture areas. It is shown that the application to the construction of rural roads is compatible with the existing technologies, including the use of CCC rollers and LWD measuring devices. The materials exhibit satisfying characteristics in laboratory evaluations, including fragmentation and post-compaction stiffness, which permits considering them for further field evaluations. The pavement layers built with recycled aggregates gives to hand enough performance under heavy traffic condition and precipitation for single or dual base layer pavements. This, together with the fact that these aggregates can be available in most areas in large quantities, provides a great momentum towards shifting from traditional materials to more sustainable alternatives. Other than considerable load-bearing performance, the chemical and environmental stability of these aggregates based on the leaching measurements, proves the soundness of these materials to be utilized in natural and farming environments.

RECOMMENDATIONS

Referring to the global trends, ecological considerations and surging demand, it is obvious that the utilization of recycled aggregates in civil engineering is increasing year after year, especially after the recent crisis of the construction sector. Decades of technical experience in using traditional natural aggregates depicts the absolute need for imperative studies on sustainable recycled aggregates to be consumed in infrastructure construction as soon as possible, to reverse the accelerating rate of natural resource exploitation.

This research envisages the potential of recycled aggregates of demolition wastes to be used in low-traffic rural roads and other farming pavements. Despite an attempt was made to offer a comprehensive study on the topic of the thesis, still there are many questions that need to be answered in further researches. Several recommendations are listed below to further expand the scope of this work.

i. This thesis is mainly focused on the pavement construction potential of the recycled aggregates obtained from CDWs. By this aim, the compactability and fragmentation resistance of the aggregates were put in to the spotlight. However, there is a need to perform more laboratory dynamic tests to complete the overall image of the various aggregate properties. As an example, the concerns such as shakedown of these aggregates under repeating loads of rural pavements could give valuable information for durability studies of these pavements.

ii. The super heavy agriculture machinery impose huge and slow loads on pavement layers. These extraordinary axle-loads will make cumulative deformation and plastic strains that ends in important damages of pavement by rutting or shoving. The effect of these heavy axle loads and their connected surface stresses could be studied in a separate case study done on the pavements constructed with recycled aggregates.

iii. The possibility of mixing the recycled aggregates obtained from CDWs and other sources such as recycled polymeric materials will make a possible step forward in sustainability and decreasing the amount of landfill wastes. Crumbled tyres are one of the wastes, which are generated in large amounts all over the world and could be utilized in pavements.

iv. In future work, the composition of semi-flexible bitu-cement composites can be optimized by performing other laboratory tests such as flexural strength and fatigue tests. These tests will give to hand a wider knowledge about the stability and mechanical properties of semi-rigid pavements constructed by these composites. Besides, additional studies should be carried out on expanding the variations of the composition percentages and should include a full-scale trial site to prove the solution feasible and verify its main engineering characteristics.

It is recommended to study new possible combinations of the implemented reinforcing geo-sandwiches such as geo-mesh and geo-grids to improve the bearing capacity and moisture drainage of the husbandry paddocks and other soil surfaces. Besides, other properties of paddocks such as herbal coverage could be studied for farming purposes.

LIST OF PUBLICATIONS

1. Pourkhorshidi, S., Sangiorgi, C., Torreggiani, D., Tassinari, P.: Using Recycled Aggregates from Construction and Demolition Waste in Unbound Layers of Pavements, Sustainability. 12, 9386 (2020) https://doi.org/10.3390/su12229386 .

2. Pourkhorshidi, S., Sangiorgi, C., Torreggiani, D., Tassinari, P.: A review of studies on laboratory evaluations of agricultural waste materials for rural and low traffic pavements, International Journal of Environmental Science and Technology (under review), submitted 2022.

3. Pourkhorshidi S., Sangiorgi C., Fathollahi A., Coupe S. J., Torreggiani D., Tassinari P., Laboratory compaction and leaching assessment of recycled aggregates for unbound pavement layers. Road Materials and Pavement Design (under review), submitted 2023.

4. S. Pourkhorshidi, C. Sangiorgi, D. Torreggiani, P. Tassinari, Assessment of construction and demolition waste materials for sublayers of low traffic rural roads, in: 11th International Conference on the Bearing Capacity of Roads, Railways and Airfields, Vol. 3, CRC Press, London, 2022: pp. 480–490. https://doi.org/10.1201/9781003222910-50

5. Pourkhorshidi, S., Sangiorgi, C., Torreggiani, D., Tassinari, P. (2023). Integration of Spot Tests and Vibratory Roller Data in Rural Road Pavement Layers Made with Recycled Aggregates. In: Gomes Correia, et.al. (eds) Trends on Construction in the Digital Era. ISIC 2022. Lecture Notes in Civil Engineering, vol 306. Springer, Cham. https://doi.org/10.1007/978-3-031-20241-4_20

6. Pourkhorshidi S., Solouki A., Torreggiani D., Tassinari P., Sangiorgi C. Laboratory characterization of bitu-cement composite recycled cold mixes as an alternative to traditional semi-flexible pavement layers. Case Studies in Construction Materials (submitted).

7. Pourkhorshidi S., Solouki A., Torreggiani D., Tassinari P., Sangiorgi C. Case study: using a geocells-aggregates sandwich layer to improve load-bearing and drainage properties of farming paddocks (to be submitted in 2023).

RESEARCH OUTCOMES