The applicability of C&D waste material in South Africa road construction

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Declaration

As the candidate's Supervisor I agree to the submission of this thesis

Durban 30/11/2015 .

I, Valentina Zedda declare that

1. The research reported in this thesis, except where otherwise indicated, is my original research
2. This thesis has not been submitted for any degree or examination at any other university.
3. This thesis does not contain other persons' data, pictures, graphs or other information, unless specifically acknowledged as being sourced from other persons.
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DETAILS OF CONTRIBUTION TO PUBLICATIONS

This research project has produced three research papers, one of which is accepted for publication, one under review and one waiting for review. These works correspond to the three main chapters of the present thesis.

I carried out these projects with critical feedback of the Professor Cristina Trois, Professor Philip Everitt and Dr Dario Scussel.

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Abstract

In contrast to developed countries, South Africa is starting to adopt the practice of using recycled rubble from civil engineering demolition works in road construction. This change is due to environmental considerations, but somewhat unique nature of the South African road construction techniques requires a careful classification of these alternative materials and a rigorous study.

In this study the possibility of reclaiming the Construction and Demolition (C&D) waste produced in the Durban Metropolitan Area was investigated. A lack of policies for the reuse of waste produced by the civil industry caused the storage of large quantities of C&D waste in the metropolitan landfill sites. In order to decrease this volume the rubble can be reused as construction material for road works. Without alteration in collection process, the C&D waste should be kept sorted according to its nature in landfill site to keep its characteristics as homogeneous as possible. Moreover, specific tests performed in this thesis confirmed the viable construction properties of this material such as non-plasticity and bearing capacity that conform to the South African construction standard.

The suitability of the C&D materials in civil works is further demonstrated by the analysis of the rubble generated by the deconstruction of the Natal Command, an ex-military area, in Durban. The demolition of the study area has followed a rigorous procedure of deconstruction. This approach allowed the principal components of the waste (Concrete and Masonry) to be kept separated. Laboratory tests accurately assessed the geotechnical properties of concrete, masonry and of a blend of them which were previously identified as suitable aggregates for unbound road base or sub-base layers. These materials are considered as A1a in AASHTO classification and as G4 in COLTO classification. In addition to the standard test of characterisation, the risk of polluting the environment was assessed.

An instrumented embankment was built in accordance with South African road compaction standards using blend material. This enabled the verification of the behaviour of C&D material in real-word working conditions. The instrumentation recorded the stresses, strains and moisture at three depths of the embankment during the passage of trucks at different predetermined speeds. The results of the monitoring were analysed and correlated to the results coming from the full performance material characterization carried out in laboratory.

This study will thus enhance knowledge of the behaviour of C&D material and also provide a useful tool to the designer in the planning stages as well as information for contractors involved in C&D road construction application.

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Chapter 1

1 Introduction

1.1 Framework

Nowadays Waste Management is a serious issue for the developing countries due to their incessant economical and demographical growth, both of which directly influence the production of refuse. Among the waste produced every day, Construction and Demolition (C&D) material generated by civil industry is predominant. This type of solid waste consists mainly of concrete, brickworks, wood, metal, paper, soils and rocks.

The C&D waste is commonly disposed in specific areas of the landfill sites. The ability to recognize this material as a resource and to identify new uses in different fields would counteract the deficiency of space in landfills. On the other hand the demand for natural aggregates for civil purposes has reached unsustainable level causing the depletion of quarries and the increasing gases emissions due to the production and transport of these materials to the construction sites. Given the global lack of resources for natural aggregate production, coupled with the intention of environmental preservation, rubble could be used as effective replacement.

Generally the waste coming from the civil sector can easily replace natural aggregates for common uses in road construction. The issues regarding the large demand of virgin material by the road industry in developing countries can be positively attenuated by diverting the large C&D waste stream to the construction sites.

The construction industry, always in search of large quantities of good quality aggregates, would seem the best field of application for this material. The C&D material, in fact, proved suitable in terms of its geotechnical qualities that allow the replacement of natural materials in different applications. For this reason European countries and the United States already encourage the reuse of alternative materials thought financial incentives to make their applications more competitive than the use of natural aggregates.

The C&D reclaim therefore reduces the waste storage in terms of time and costs, clears landfill sites, prevents the dereliction of land prevents the impoverishment of the natural resources.

1.2 Problem statement

The Republic of South Africa has an emerging market with a central role in the economy of the whole African continent. For this reason this nation is about to face the same environmental problems of developed countries. However, due to the specific history of this nation, only few cities have undergone to a significant growth. The rest of the human settlements are composed of small cities, townships and rural farms. This configuration is cause of difficulties in the coordination of a national waste management system. However, the knowledge of the issues previously addressed in different nations places South Africa in a position to anticipate and deal with them by means of new and more environmentally friendly technologies.

The waste produced is usually roughly disposed in legal landfills or illegally dumped in rural areas, affecting the surrounding environment and obstructing the possibility of its collection and reuse. Moreover, the shortages of recycling facilities in the official landfill sites and lack of administrative skills in the small municipalities also slow down the growth of a national recycling segment.

The main components of waste, as well as in other countries, derive the leftovers of civil engineering works generated during construction and demolition processes. The C&D material, when not stockpiled, is generally used for backfilling, landscaping, site levelling and landfill purposes. However, these applications are not able to dissipate the large quantities of C&D material that overfill the landfills areas. The constant request of aggregates for construction and maintenance suggests using this waste would contribute to the development of South Africa.

The Durban Metropolitan Area and its main landfill, run by eThekwini, were taken as example. This research flanks to another about the control, the management and the treatment of landfill emissions from the same University to complete the framework of the waste management. In fact, the C&D waste is one of the main streams which go to disposal.

1.3 Scope and objective of the thesis

The aim of this research is to verify whether the recycling of C&D waste is practicable in South Africa given the present conditions and management of the existing landfill sites, the characteristics of incoming waste stream and the national environmental legislations.

Even though the use of C&D waste is universally suggested as source of aggregates for road construction, its use is still not much considered in the South African road pavement industry. However new national guideline suggest the use of alternative materials and some applications of C&D in this field were already in effect but, for the proper inclusion in the South African guidelines, more accurate studies are necessary.

The South African road pavement design, developed in the Seventies, is in fact completely different from the universally recognized American and European approaches. For this reason it is not possible to simply import the results of the experiences made in those contexts without a critic verification of the real applicability in the present background.

The South African Pavement Design Catalogue provides three types of structures for flexible pavements categorised depending on the base type. It can be cement or bitumen stabilized (respectively called cement and hot-mix asphalt base) and granular (granular base).

The simplest and less expensive option is the granular base because it does not require any technique of improvement for its application. For this reason the physical and mechanical characteristics of the aggregate used must be very good.

The objectives of this research is to determine the applicability and the assessment of the behaviour of C&D materials in view of replacing natural aggregates in unbound granular bases and sub-base. For this purpose, in this thesis, the amount of C&D waste produced in the metropolitan area of Durban is determined and predictions on the impact this resource would induce if introduced in the construction market are made. The scope is the management of C&D waste in a cradle to cradle design point of view, focusing on its waste stream, its properties and its reuse in road pavement. This material is then analysed in accord to the South African requirement for granular base and sub-base materials and tested in a real working load application.

This research on C&D waste materials want to lead to the following achievements:

- South Africa, although the recycling of C&D waste is not performed as well as in other countries, has considerable potential for its reuse and recycling due the amount of civil works in the country and the waste produced from those. The Bisasar Road landfill, in Durban was taken as an example. The quantity of C&D material is calculated comparing with the entire amount of the incoming waste.
- Confirms that C&D materials from landfill sites and from the demolition of buildings are not plastic and are equivalent to A1a in the HBR Soil Classification

System. It may be equal to G3/G4 as well as G5/G6 aggregates according to South African Soil Classification System, which highlights their heterogeneous characteristic.

- The durability of these materials is less than natural aggregates probably due to their high water absorption. A correlation was investigated between water absorption and durability tests such as LAA and ACV.
- The applicability of a specific blend of C&D material, prepared by 75% of masonry and 25% of concrete, was studied in an experimental instrumented embankment which shows that its behaviour is the same as natural aggregates for shorts and long term.
- Young's modulus, although it was calculated in different ways, has a reasonable and fairly high value. It could be compared to a G3 material according to Theyse in South African soil classification system.

1.4 Thesis structure

This thesis consists of 6 Sections: introduction, literature review, three main chapters and conclusions. The present section is an overview of this research and explains the organization of the following Chapters.

Chapter 2 presents a review of the various disputes regarding waste management and solutions adopted to reduce the amount of waste in landfills. This section is specifically focused on the determination of characteristics and recycling approaches of Construction and Demolition waste material and applications in road construction. Previous studies on environmental and structural strengths and weakness in the use of this alternative material in civil engineering are also presented.

The three main Chapters (3, 4 and 5) were written as set research papers ready for or already published in international scientific journals.

Chapter 3 describes the South African economic growth and the waste management solutions activated for reducing its effect to the surrounding environment. The condition and the management implemented at the Bisasar Road landfill site, located in Durban and one of the most structured landfill sites in the country, have been investigated and used as base for the development of an integrated recycling system to manage the huge amount of C&D waste received every day in the landfill. The proposed approached would ensure a material of more homogeneous characteristics without a radical alteration of the present collection process. In order to reduce the heterogeneity caused by an unstructured stockpiling of the incoming waste, a sorting procedure is suggested. The reliable knowledge of a C&D waste intended for civil engineering is in fact essential. A preliminary classification of the C&D stored in the landfill site was also performed. The results of the laboratory tests performed confirmed the possibility of using this material for replacing natural soils in unbound granular layer complying with the South African specifications.

A more accurate study of the geotechnical properties of a C&D material is presented in Chapter 4. Concrete and masonry, derived from the deconstruction of an ex-military area in Durban, and a blend of these two were intensively investigated in accord to South African and international road engineering standards. The results of this analysis demonstrated good quality of these materials in in terms of shear resistance, plasticity, bearing capacity and durability and placed it as A1a material accordingly to the HRB classification and as G4 in the South African COLTO and TRH14 classifications.

Chapter 5 describes the behaviour of C&D material in real working conditions. An instrumented smart road embankment, entirely built with the C&D blend described in the previous chapter, was monitored for a year. In specific, deformations and variations in pressure, temperature, moisture content within the embankment were recorded at the passage of trucks of different weight. Further in situ tests such as Falling Weight Deflectometer (FWD) and density by means of nuclear gauge were also periodically carried out during the year. The results of this study have been compared to those coming from a similar test performed in Italy to a material of similar characteristics.

Chapter 6 summarizes the conclusions of the main chapters and give some recommendation for practical applications and suggestions for further studies.

1.5 Bibliography

- Poon C.S., Management of construction and demolition waste. 2007. Waste Management 27 (2): 159-160
- Franklin Associates. 1998. Characterization of building-related construction and demolition debris in the United States, Prepared for The U.S. Environmental Protection Agency Municipal and Industrial Solid Waste Division Office of Solid Waste, Report No. EPA530-R-98-010.
- Inyiang H. 2003 Framework for Recycling of Wastes in Construction. Journal of Environmental Engineering 129: 887–898
- Kourmpanis, B., Papadopoulos, A., Moustakas, K., Stylianou M., Haralambous K.L. and Loizidou, M. 2008. Preliminary study for the management of construction and demolition waste. Waste Management & Research 26 (3): 267–275
- Carmody, J., Strong, R. and Jacobson, R. 2011. The Minnesota Site and Building Carbon Calculator

- Macozoma, S.D. 2006. Developing a self-sustaining secondary construction materials market in South Africa. A dissertation submitted to the University of the Witwatersrand, to fulfill the requirements for the degree of Master of Science in Engineering. Faculty of Engineering and the Built Environment. Johannesburg, South Africa. University of the Witswatersrand
- Committee of State Road Authorities, TRH4 (1996): Technical Recommendations for Highways - Structural design of flexible pavements for interurban or rural road
- Committee of Land Transport Officials (COLTO) (1998) Standard specifications for road and bridge works. Pretoria: the South African Institution for Civil Engineering (SAICE)
- Committee of State Road Authorities. 1985. Technical Recommendations for Highways – Guidelines for road construction materials TRH14. Pretoria: Department of Transport.
- South African National Road Agency. 2014. South African Pavement Engineering Manual (SAPEM). Republic of South Africa 2° edition

Chapter 2

2 Literature Review

2.1 C&D Waste Material

2.1.1 Definition and Classification

Construction and demolition (C&D) waste material is a type of solid waste generated from refuse of the civil engineering industry (US EPA, 2009). This kind of waste consists of either residual material from residential or non-residential construction projects. However, the origin can also be the reaction to natural disasters as earthquakes, tornados, hurricanes or floods (Macozoma, 2006).

The waste produced by the civil engineering sector is mostly composed of concrete, brickworks, soils, rocks but also glass, plastics, metals, lumber, cardboard, drywall, insulation, roofing, plumbing and electrical materials.

It has been observed that the composition of a C&D waste is directly influenced by the type and the purpose of the originating structure or superstructure. At the same time, the C&D waste associated to the demolition process shows different characteristics from one originated in the construction stage. For instance the properties of two C&D wastes coming from different scenarios can be equivalent only under very strict conditions. Some of the parameters determining the final characteristics of a C&D waste, functions of the originating structure, can be grouped as follows (Kourmpanis et al, 2008):

- Period of construction.
- Form of construction.

- Main materials used for the construction.
- Techniques that are applied for the construction.
- Techniques that are applied for the demolition.
- Historical, cultural, economic value and importance.

Another peculiarity of this material is the intrinsically high heterogeneity which is mostly due to its anthropic origin. Moreover, the waste stream to a landfill site, the process used for disposal and the different definitions given by the national legislations are further cause of varied composition (Kourmpanis et al, 2008).

The C&D waste sources are commonly categorized accordingly to the following classification system (Symonds Group Ltd. 1999):

- Waste arising from the total or partial demolition of buildings and/or civil infrastructure: this is the most heterogeneous group given the difficulty is in sorting the produced waste, which consists of concrete, wood, tiles, masonry, ceramics, coats, metals, wires, soils, gravels, insulation and sanitary materials etc.
- Waste arising from construction and renovation of buildings and/or civil infrastructure: this group consists of cement, bricks, wood, tiles, packaging and materials for the preparation of a construction site.
- Waste generated from land levelling, excavations, civil works or foundations: produced in mostly civil works and in particular geotechnical works, it consists in soils, gravels, sands, rocks, and clay.
- Construction and maintenance of roads: bitumen, cement, aggregates, natural soils are common material while metals and plastic are found very rarely.

Although in most common cases the use of these categories is generally sufficient, a more accurate classification was introduced in 2002 in the European Waste Catalogue (EWC). In Chapter 17 of this document, the C&D materials is clearly divided into 9 more homogenous groups, each one arranged in more specific subcategories, as shown in Table 2-1. Unlike other classification approaches proposed in other countries, it also includes hazardous wastes, marked with an asterisk (*), following the Directive 91/689/EEC.

Table 2-1 Classification of C&D waste materials

17 CONSTRUCTION AND DEMOLITION WASTES (INCLUDING EXCAVATED SOIL FROM CONTAMINATED SITES)	
17 01	**concrete, bricks, tiles and ceramics**
17 01 01	Concrete
17 01 02	Bricks
17 01 03	tiles and ceramics
17 01 06*	mixtures of, or separate fractions of concrete, bricks, tiles and ceramics containing

	dangerous substances
17 01 07	mixture of concrete, bricks, tiles and ceramics other than those mentioned in 17 01 06
17 02	**wood, glass and plastic**
17 02 01	Wood
17 02 02	Glass
17 02 03	Plastic
17 02 04*	glass, plastic and wood containing or contaminated with dangerous substances
17 03	**bituminous mixtures, coal tar and tarred products**
17 03 01*	bituminous mixtures containing coal tar
17 03 02	bituminous mixtures containing other than those mentioned in 17 03 01
17 03 03*	coal tar and tarred products
17 04	**metals (including their alloys)**
17 04 01	copper, bronze, brass
17 04 02	Aluminium
17 04 03	Lead
17 04 04	Zinc
17 04 05	iron and steel
17 04 06	Tin
17 04 07	mixed metals
17 04 09*	metal waste contaminated with dangerous substances
17 04 10*	cables containing oil, coal tar and other dangerous substances
17 04 11	cables other than those mentioned in 17 04 10
17 05	**soil (including excavated soil from contaminated sites), stones and dredging spoil**
17 05 03*	soil and stones containing dangerous substances
17 05 04	soil and stones other than those mentioned in 17 05 03
17 05 05*	dredging spoil containing dangerous substances
17 05 06	dredging spoil other than those mentioned 17 05 05
17 05 07*	track ballast containing dangerous substances
17 05 08	track ballast other than those mentioned in 17 05 07
17 06	**insulation materials and asbestos-containing construction materials**
17 06 01*	insulation materials containing asbestos
17 06 03*	other insulation materials consisting of or containing dangerous substances
17 06 04	insulation materials other than those mentioned in 17 06 01 and 17 06 03
17 06 05*	construction materials containing asbestos (18)
17 08	**gypsum-based construction material**
17 08 01*	gypsum-based construction materials contaminated with dangerous substances
17 08 02	gypsum-based construction materials other than those mentioned in 17 08 01
17 09	**other construction and demolition waste**
17 09 01*	construction and demolition wastes containing mercury
17 09 02*	construction and demolition wastes containing pcb (for example pcb-containing sealants, pcb-containing resin-based floorings, pcb-containing sealed glazing units, pcb-containing capacitors)
17 09 03*	other construction and demolition wastes (including mixed wastes) containing dangerous substances
17 09 04	mixed construction and demolition wastes other than those mentioned in 17 09 01, 17 09 02 and 17 09 03

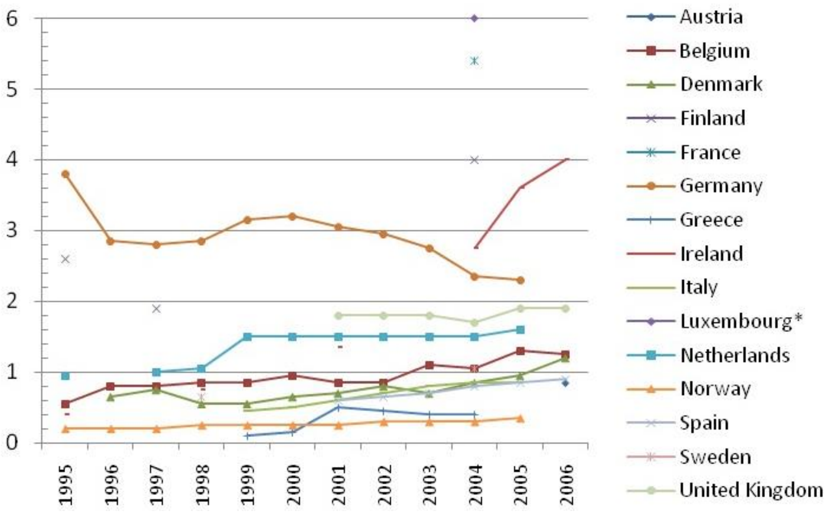
The table, however, should be adjusted if used as a support for a better C&D materials classification that can be used in road pavement materials field. In particular paragraph 17 01 includes a list of suitable materials which have similar properties to the natural materials used in the subgrade, bases and sub-bases in road pavements. For a more homogenous classification concrete, bricks, tiles and ceramics should divide by type, then giving each limit values and uses.

2.1.2 C&D waste streams

The annual world production of C&D waste is quantifiable in 2-3 billion tons (Leite, 2001). This amount is the sum of the materials coming from the numerous construction, demolition, renovation and road construction projects which represent the major waste streams of every country (Arslan et al, 2012).

The comparison of the declared national productions needs specific considerations since it is always influenced by a large number of country-specific factors. Economic growth rate, natural catastrophes, cultural and social aspects, different classifications used for defining a C&D waste and identified approaches for recording production and volumes landfilled (Kourmpanis et al, 2008) are some of the most important. For instance in 2004, the city of Hong Kong generated 20 million tons of C&D waste (Poon et al., 2007) while the entire Australian civil industry produced only 15.1 million tons (The Blue Book - Australian Waste Industry, 2008). In the same way Franklin Associates (1998) registered more than 120 million tons in the USA while Leite (2001) observed a comparable amount in Japan, 86 millions, probably due to the reconstruction following 6.7 M_w Geiko earthquake in Hiroshima.

Figure 2-1 shows the C&D waste generated per inhabitant by the European countries from 1995 to 2006 (Almut et al, 2008). In 2008 the total amount of the European C&D production reached more than 887 million of tonnes (Sáez et al, 2011)



* Real data for 2004 is 15.2.

Figure 2-1 Tonnes of C&D per inhabitant (Almut et al, 2008)

C&D waste stream is especially large in developing countries because of their unceasing efforts in modernization and improvement of services such as road networks, residential buildings, hydraulic systems, etc. China, which is today the second world leading economy, generates 2.4 billion tons of C&D every year (Dong et al, 2001). The Indian construction industry, which is the second largest national business after agriculture, can landfill 24 million tons of rubble per year (Shrivastava et al, 2009).

2.1.3 C&D waste management

2.1.3.1 Definition of Waste Management

The term "waste management" describes the human process of monitoring the cycle of a waste from generation to landfill disposal (US EPA, 2009). Moreover, with the implementation of an appropriate waste management system, the prediction of the waste stream characteristics and volumes is also possible. The knowledge of these allows the application of specific and more accurate actions which is the key to transform refuses into resources (Wang et al, 2004).

The first attempt of waste management dates back to Neolithic times (about 5000 years ago) when the tribes dug sewers for transporting the waste generated in the villages to the nearest body of water. This approach was improved by the Romans who built canal networks within their cities to transport refuse to the sea (Leite, 2001). Nevertheless, this evolution implied growth of population and goods consumption, causing a significant increase in waste produced. In this context waste management has become a complex issue because of the large volumes involved which, if not properly addressed, also have the potential to cause human and animal epidemics. For this reason the management of waste should follow specific procedure to match the development rate of a country. In these contexts, the correct implementation and the improvement of the existing management approaches is an essential part of the achievement of sustainable development (Paschoalin et al, 2012).

Symonds Group Ltd. (1999) suggested a list with four different destination options for C&D materials:

- Landfilling: off-site landfilling of segregated or unsegregated waste materials;
- Incineration: off-site incineration with or without energy recovery;
- Re-use: re-use on-site or off-site for the original intended purpose;
- Recycling: on-site or off-site processing to recover high value saleable materials; recycling on-site or off-site for a low-value purpose (including non-essential land raising).

Part of the produced waste can be successfully burned to produce energy or can self-degrade in a short period of time. However, most of the waste materials are not biodegradable. For these materials the research of new uses is the only way to prevent endless environment pollution or the depletion of all the current and future landfill areas. The Construction and Demolition materials are clearly included in this category (Maczulak, 2010).

A good waste management system should always consider multiple different processing approaches. The impact of the different systems is described in the Waste Hierarchy Method which classifies the recycling options used in order of importance (Australian EPA, 2009). The application of correct solutions for the specific case is the base for increasing the efficiency of the recycling process (Costa, 2003). The Waste Hierarchy which was included in the European Union Waste Framework Directive 2008 for the first time, graphically represented in Figure 2-2, involves a series of 6 actions for waste minimisation. These options are usually represented as elements of a pyramid where those most positive for the environment are placed at its top.

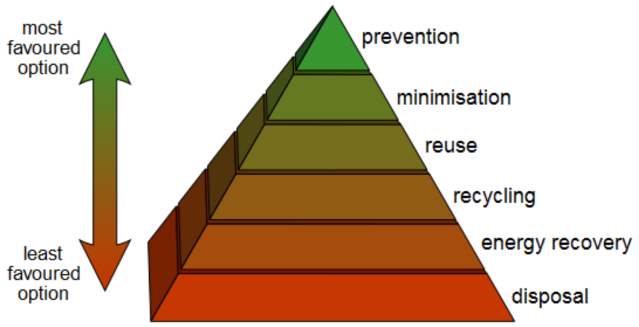


Figure 2-2 the Waste Hierarchy (European Union Waste Framework Directive, 2008)

- Prevention: reduce the generation of waste or keeping items for long time
- Minimization: using less material in design and manufacturing and reduce hazardous products.
- Reuse: use materials again for their original purposes

- Recycling: use materials for purposes other than their original one
- Energy Recovery: operation for producing energy from waste
- Disposal: stockpiling materials without any treatment or energy recovery

The application of the Waste Hierarchy has the most positive effect when applied to large waste streams.

In the Waste Hierarchy the two important actions are Prevention and Minimization of the generation of a waste. These options have the highest influence on the amount of waste produced but are not able to completely interrupt the flow of waste to landfill. The most efficient options for the waste still produced are the establishment of new uses or the transformation in energy. If all these actions are properly utilised, the amount of material conveyed to the landfill sites will drastically decrease.

2.1.3.2 Recycling and Reuse

In the case in which the rational management of natural resources is not sufficient to avoid a significant wastage, the best feasible option is the reuse or recycling of the waste resource.

The practice of reusing and recycling rubble from construction dates back to the Romans and Phoenicians who used to crush masonry as concrete aggregate. However, only in 1928 systematic studies started for assessing the actual ratio of natural resource/crushed masonry in concrete production (Paschoalin et al, 2012). The need of construction materials in Europe, Japan and other countries for the reconstruction following the World War II was the starting point for the first organised recycling activity in the construction sector. At that time, the large amount of rubble due to bombardments proved to be an excellent and cheap base for building materials (Poon et al, 2007).

These original nations along with the addition of some states in the USA are still the core of the C&D recycling sector (Poon et al, 2007). Some nations of the EU such as Netherland, Belgium and Denmark are today able to reclaim more than 80% of the C&D waste stream generated (European Environment Agency, 2002). The percentage of recovery of each European Members in 2002 is listed in Table 2-2.

Table 2-2 Management of C&D waste in European countries (EEA, 2002)

Country	Quantity (10^6 tonnes/ year)	Percentage of recovery (%)	Percentage of final disposal (%)
Germany	59	17	83
United Kingdom	30	45	55
France	24	15	85
Italy	20	9	91
Spain	13	< 5	> 95
Netherlands	11	90	10
Belgium	7	87	13
Austria	5	41	59
Portugal	3	< 5	> 95
Denmark	3	81	19
Greece	2	< 5	> 95
Sweden	2	21	79
Finland	1	45	55
Ireland	1	< 5	> 95

These, already excellent, results can still be improved by making use of more innovative approaches. The Institution of Recycling Network (2005) proved that almost all the wastage coming from construction sites is recyclable; generally about the 90-95% can be easily reused. The reclamation of the remaining percentage is not convenient because of the need of special and expensive treatments that reduce the interest of the market. In fact, the proposal of the European Community is to achieve a recovery of 70% by weight by 2020 (Bio Intelligence Service, 2011)

The data in Table 2-2 was overcome and results are shown in a report by Bio Intelligence Service (2011). This was entrusted by European Community for understanding the magnitude of the amount of waste generated in Europe that are reused, recycled or the potential for improvement. Moreover its study tries to identify concerns the management of C&D waste and improvements of reuse and recycle.

Bio Intelligent Service put together the data from two sources (UBA 2009 & ETC/RWM 2009) for providing recycling and recovery rates of C&D waste in some European countries. Table 2-3 and Table 2-4 show the upgraded data.

Table 2-3 Comparison of reported recycling rates for C&D waste from two recent sources (UBA 2008 & ETC/RWM 2009)

Source	UBA 2009			ETC/RWM 2009		
Country	Year	Arising (million tonnes)	% re-used or recycling	Year	Arising (million tonnes)	% re-used or recycling
Austria	2004	6,6	76%	2006	6,7	60%
Belgium		12,3	86%	2004	11	68%
Belgium-Brussel	2000	1,2	59%	-	-	-
Belgium-Flanders	2006	9	92%			

Belgium-Wallonia	1995	2,1	74%			
Bulgaria	-	-	-	2004	3	
Cyprus	-	-	-	2004	0,4	100%
Czech Republic	2006	8,4	30%	2006	11,8	23%
Denmark	2003	3,8	93%	2004	21,7	94%
Estonia	2006	2,4	73%	2006	0,7	92%
Finland	2004	1,6	54%	2004	20,8	26%
France	2004	47,9	25%	2004	342,6	62%
Germany	2002	73	91%	2006	192,3	86%
Greece	1999	2	5%	2004	4,1	-
Hungary	-	-	-	2006	5,4	16%
Ireland	2005	2,3	43%	2006	16,6	80%
Italy	2004	46,5	-	2004	46,3	-
Latvia	-	-	-	2006	0,1	46%
Lithuania	2006	0,6	-	2006	0,6	60%
Luxembourg	2005	7,8	46%	2004	27	-
Malta	-	-	-	2004	0,8	-
Netherlands	2005	25,8	95%	2005	25,8	98%
Poland	2000	202	75%	2006	16,8	28%
Potugal	1999	3	5%	2004	11,4	-
Romania	-	-	-	2005	0,4	-
Slovak Republic	-	-	-	2004	1,4	-
Slovenia	2005	1,1	53%	-	-	-
Spain	2005	35	-	2006	38,5	14%
Sweden	2006	11	-	2004	10,2	-
UK		100,4	82%	2006	114,2	65%
UK-England	2005	89,6	80%	-	-	-
UK-Scotland	2003	10,8	96%	-	-	-
average for x countries with available data			86%			65%
total amount of C&D waste on which estimation is based			252,7			820,2

Table 2-4 Calculation of the average recycling rate of C&D waste (BIOIS, based on own assumption and data reported by ETC/RWM 2009 and UBA 2008, or individual estimations)

Country	Arising (million tonnes)	% re-used or recycling
Austria	6,60	60%
Belgium	11,02	68%
Bulgaria	7,80	0%
Cyprus	0,73	1%
Czech Republic	14,70	23%
Denmark	5,27	94%
Estonia	1,51	92%
Finland	5,21	26%
France	85,65	45%
Germany	72,40	86%
Greece	11,04	5%
Hungary	10,12	16%

Ireland	2,54	80%
Italy	46,31	-
Latvia	2,32	46%
Lithuania	3,45	60%
Luxembourg	0,67	46%
Malta	0,80	-
Netherlands	23,90	98%
Poland	38,19	28%
Potugal	11,42	5%
Romania	21,71	-
Slovak Republic	5,38	-
Slovenia	2,00	53%
Spain	31,34	14%
Sweden	10,23	-
UK	99,10	75%
EU 27	531,41	46%

Moreover, a main motivator for an extensive reuse or recycling of this C&D waste is having a competitive price with that of standard virgin materials. The following equation can be used for the evaluation of the competitiveness of a C&D material ready on site for use (The Institution Recycling Network, 2005)

$$C_{rm} + C_t + C_{ex} < C_v + C_{tv} \quad (1)$$

Where:

C_{rm} Cost of recycled material at the centre

C_{trm} Cost of transport from the centre to the site

C_{ex} Extra cost

C_v cost for the production of virgin material

C_{tv} cost of transport for the virgin material from the quarry to the site

The previous disequation leans often towards the right term of the same, due to magnitude of the parameter C_{rm}. For counterbalance the effect of this parameter, the recycling is promoted by the introduction at the administrative level of taxes on *exploitation* of natural *resources.* In the same way, for discouraging the use of virgin aggregates, economical compensations are applied for the use of C&D materials in civil works (Inyang, 2003)

2.1.3.3 The Sorting procedure

The benefits resulting from the reuse and recycling of C&D materials grow proportionally to the homogeneity of the waste used. In addition to the high degree of heterogeneity, the large number of parameters influencing the behaviour of a C&D waste (mineralogical composition, density, particle size distribution, freeze and thaw durability, presence of environmental pollutants) (Deutsche Institut fur Normung, 2002) makes the ordinary sampling techniques DIN EN 932-1:1996 used for representing the average properties of natural aggregates insufficient (Angulo and Muller, 2009).

The Theory of Sampling for heterogeneous materials (Peterson et al, 2004), which was experimentally validated in 2009 (Angulo and Mueller, 2009), is today commonly implemented to determine the representative mass necessary for the proper characterization of a secondary raw material.

In order to reduce the inhomogeneity of this man-made resource, numerous sorting techniques have been developed to separate the individual components of refuse (Poon et al 2001). These sorting process, generally, incorporate different methodologies depending on composition and origins of the waste (new construction, renovation, demolition or deconstruction) (U.S. EPA, 2009). However, these approaches are unfortunately still complex and expensive due to the significant resources and technologies required to achieve valuable results.

The sorting procedure generally does not consist of only one single methodology, the correct approach should consider the sequence of different processes (Huang et al 2002).

The most common sorting approaches are following listed:

- Visual sorting: it is initial screenings, workers, by means of their eyes, remove papers, metals, glass, plastics with their hands.
- Optical detector: automatic machine that separates glass by colour
- Bar screening: separation of materials by size
- Density classification: to separate heavy aggregates from mortar
- Metal separator: automatically separate ferrous material by means of magnetic system
- Air classification process: separate light particles, using an air jet or rarely liquid jet from the top
- Dual-energy X-Ray transmission: x-ray scanning which evaluate the properties of materials for separating of scrap non-ferrous metals
- Dry or wet Heavy Medium Separation: it is a gravity separation process for isolating materials with different density using a centrifuge with or without liquid.

- Air jigs: invented for the mining industry for separating stone from coal. Nowadays it is a common density separator that by means of pulsating air jets allows the materials stratification.
- Wet Jigging: it follows the same procedure of air jigs but materials are placed in a tank

The length of the operative sorting sequence can be reduced by directly implementing preliminary sorting procedures on site or by providing deconstruction in place of demolition procedures (Poon et al, 2001). In this way the material transported to landfill will already be stockpiled into partially homogeneous volumes.

2.1.4 Common uses of C&D wastes in Civil Engineering

The ability of a nation to reuse and recycle the waste produced plays an important role in the modern economy. The European Union continuously promotes the use of recycling aggregates in different engineering applications. For this purpose, classification systems for an evaluation of their physical characteristics (European Commission, 2002) and guidelines for the choice of the best field of application (Solis et al, 2009) or the proper processes of reuse (Symonds Group Ltd, 1999) are constantly developed and improved.

C&D raw materials are largely employed in civil works as primary construction materials (Duggal, 2003) where they can in fact either partially or completely replace natural aggregates (Bairagi, 1993). The applicability of a waste product in an engineering application is proportional to the degree of affinity between former and expected use after the recycling process. For this reason rubble reclaimed from concrete applications can be easily reused for the production of non-structural (Brito et al, 2005) or structural concrete (Gomes and Brito, 2009) with remarkable success. Mixed rubbles are commonly employed for more general purposes. Typical applications are structural or back filling material for retaining structures or basal reinforcement for standard or marine foundations (Yeung et al 2006). Sometimes, the finer part of a C&D waste is the main component for the manufacturing of bricks and mortar (Sanchez et al, 2009).

Nevertheless, the experience gained in the Netherlands has shown a high degree of applicability of C&D in road construction. In that region, over 90% of the aggregates used in roads are reclaimed waste (Hendricks and Jassen, 2001). The works in this field demonstrated that road construction and rehabilitation have become the most environmentally and economically suitable application for a C&D recycled waste (Vegas et al, 2008 - Wathne and Smith 2007).

2.1.5 Environmental impact

The applicability of C&D waste as building material is widely demonstrated by several studies and applications, some of them mentioned in the previous section of this Chapter. The use of this secondary raw material, however, brings also a relevant contribution to the protection of the environment.

As mentioned earlier, the recycling practice reduces the need of virgin material and gives a real contribution for preserving the already scarce reserves of natural resources. The civil engineering sector, in fact, relies on the supply of *construction aggregates extracted by quarries that* are not able to keep the production equal to the current demand and the environmental laws commonly issued by governments have also complicated the procedures for the opening of new quarries. These factors caused the increase in prices of the virgin construction aggregates (Inyang, 2003), disclosing new opportunities for the introduction of alternative solutions in civil construction.

The reuse of C&D materials allows also for the reduction of the energy and the amount of accessory constituents required for the production of construction aggregates (Dolan et al, 1999). It has been estimated by international research that the construction industry is cause for the global consumption of 12-16% of fresh water, 25% of wood raised, 30-40% of energy, 40% of virgin materials extracted and it is the source of 20-30% of the total greenhouse emissions (GHG) (Macozoma, 2006).

The production of aggregates and the transport from the quarry to the construction sites is in fact a significant source of GHG emissions, the main responsible for the environmental global warming (Kyoto Protocol, 2011). The three most significant greenhouse gases released in the atmosphere are carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) which, together, contribute for the 98% of the total emissions (Carmody et al 2011). The processes of extraction, crushing, screening of aggregates and the construction and the demolition of civil works are cause of considerable CO_2 emission due to the use of heavy, sometimes dated, equipment for the production and, especially, for the transport of aggregates (Fernandez, 2008). Smaller percentage of methane gas, resulting from the reaction of the organic decomposition of C&D waste, is observed in the waste disposed in landfill areas.

The correct management of the secondary raw materials coming from construction and demolition projects can significantly reduce the carbon emission (Zammataro, 2010) and, in some case, results in real zero-emission engineering approach (Carmody et al 2011).

The non-biodegradability of waste produced by the civil construction industry is identified as a major cause for the lack of storing space in landfills. This problem extends, of course, also on the landfilling of the general waste. However, environmental policies, also in this case, discourage the opening of landfills in addition to those already existing in the territory. For this reason, the reuse for construction purposes of the material already stockpiled in landfills and the application of technologies to intercept the waste streams before being transported to a landfill site are the only active ways for extending the life span of the existing landfills (Wang et al, 2004). The significant results so far achieved in this area give further motivations for investigating additional and more efficient uses for this resource.

2.1.6 The use of C&D waste in South Africa

The Republic of South Africa is a country of great traditions that, after a long period of stagnation due to the economic sanctions imposed during apartheid, is today playing a fast and impressive development. It is part of CIVETS (Colombia, Indonesia, Vietnam, Egypt, Turkey and South Africa), an acronym coined by Robert Ward (Director comprehensive forecast of the Economist Intelligence Unit EIU) in 2009 (Moore, 2012), which represents the group of countries with emerging markets that are recalling the route previously taken by the BRIC (international political organisation of leading emerging economies included Brazil, Russia, India, China) (Geoghegan M. 2010). The role of South Africa is also central and driving for the economy in all the African continent and this is the reason why it was accepted into the G8+5, the eight major economies plus five important emerging countries. A major function of this organization is also to encourage the cooperation of the member nations for reversal or mitigation of the process of Climate Change. For encouraging and promoting a sustainable development, it hosted The 17th Conference of the Parties (COP17) which took place in Durban from 28th of November till 9th of December 2011

Only recently the Republic of South Africa started developing specific policies to protect the environment and its habitat (The Government of the Republic of South Africa, 2011).However, this nation must deal with the expectations of a developing country where an acceptable development and lifestyle has not been yet achieved by the whole population, in particular in the areas far from the principal cities. The aim of the central government is to guarantee the greatest number of services to society but, at the same time, reduce wastage and support policies of sustainable development. A major challenge for the government is to improve the attitude towards environmental solutions by means of specific laws and regulations, taxation or subsidies without stopping the growth necessary for the achievement of adequate quality of life and services by the population (Wood, 2011).

South Africa still has not implemented a coordinated system of waste management and any waste is disposed in general landfills, although it is stored in designated areas. However, only the largest and organized landfills, which are generally nearby developed cities, can label and weigh the amount of waste at the entrance. The system implemented so far it is not able to support a process of recycling throughout the national territory, for the development of a sustainable waste management system will need to aim for the growth of specialised sectors interconnected with each other (Tadesse, 2010).

The C&D waste is the major national stream and it is estimated attaining around 5-8 million tonnes every year (Macozoma, 2006) with negligible reclamation. The C&D material is recycled only in low level applications such as backfilling, landscaping, site levelling and other landfill purposes (Macozoma, 2006).The approximation of the data available derives from the lack of facilities and the difference in the classification processes followed by the different municipalities.

2.2 Introduction to Road Construction

Roads are vital for civil society as they facilitate the mobility of people and goods across the world (Morse and Green, 2009). Road Systems also include interchanges, junctions crossing, bridges, tunnels or supporting structures (Organisation for Economic Co-operation and Development, 2002).

In old age, roads were simply paths compacted with materials found in loco which were travelled by people and their animals. Only after the Greek and Roman civilization an organic approach to road construction was introduced. The Roman road pavement required the excavation of a trench, 45-60 cm deep and 4-6 meters wide, filled with a series of compacted lime mortar bounded layers of soil, stone and sand. On top of this base layer, big basaltic or calcareous rectangular slabs are placed with gravel or sand filling the gaps among them. This road structure allowed long life, less maintenance and dry surface in case of rain (Corbishley, 1986).

However as the progress goes on the roads had to be developed to deal with new vehicles and increasing flows. Firstly Macadam invented a new method of road building in the XVIII century then the roads changed again when motorised transport and rubber tyres had been commercialized in Nineties (South African National Road Agency, 2014). So tar was spread over the road surface to keep in place the stones and to obtain a smooth surface. Figure 2-3 show the development of road pavement aggregates, vehicles technology traffic versus time.

In South Africa, Thomas Bain was the pioneer road-builder who constructed roads and 23 major mountain passes, nearly all in the Cape Province.

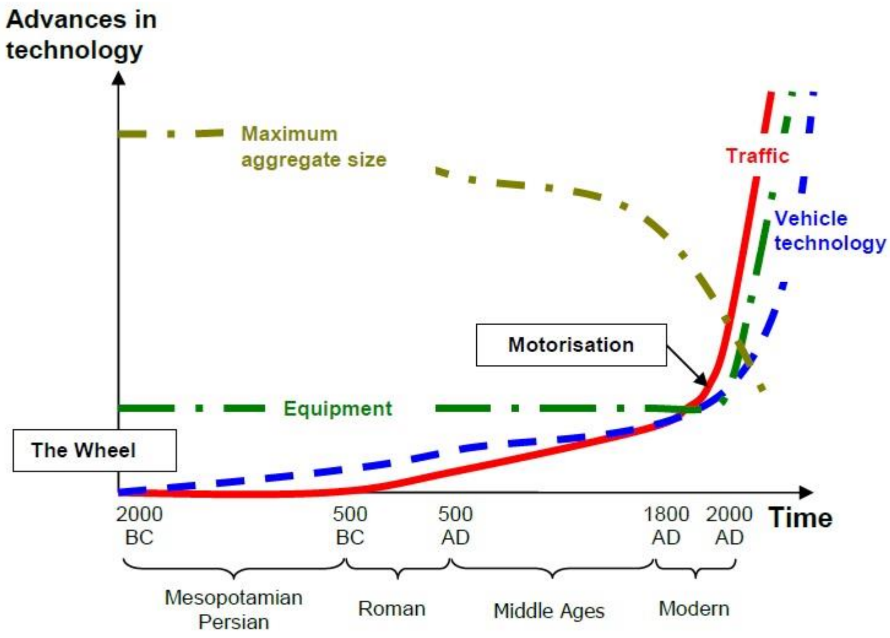


Figure 2-3 Conceptual impact of technological developments on roads (South African National Road Agency, 2014)

Nowadays the list of minimum roads requirements has obviously evolved. A modern road may at least provide the following requisites (Probati, 2008):

- Withstand traffic loads without any failure or other dangerous changes on the surface;
- Ensuring the comfort and the safety of drivers running on a surface with suitable characteristics of regularity and grip;
- Protect the layers underneath (generally the subgrade) by the weathering.

The contemporary approaches require that the roads are based on foundation layers of good load-bearing characteristics. In order to facilitate this it is often necessary to dig out for competent materials or make use of ground improvement techniques. Starting from the competent level, successive layers are made by aggregates compacted are to optimal, specific density / water content ratio, which will return the request bearing capacity, up to the desired level. Then a hot mix asphalt or concrete slabs is placed on the top to get the requirements of comfort and protection of the underneath unbound layers.

Roads have different structures depending of their level of service (LOS) which is in function of the vehicle streams (Olivari, 1994). The LOS is an estimation of traffic flow and performance level of a transportation system. A road with high LOS requires better quality materials and construction techniques than a lower LOS level road. However, regardless of the intended use, a road embankment may always be erected making use of proper techniques and suitable construction materials (Annunziata et al, 2004).

Generally the pavement consists of three components: surface, road-base and foundation (Roger, 2003).The introduction of new regulations and new designing approaches the layers names have been changed. Surface course and binder course are part of the surfacing, base is the new term that corresponds to the road base and sub-base while capping, which lay down on the subgrade, is part of the foundations (Copson et al, 2004). The capping is a layer for protecting the subgrade from damage and its top face is the plan for the road structure. Figure 2-4 shows an example of vertical distribution of a typical road embankment.

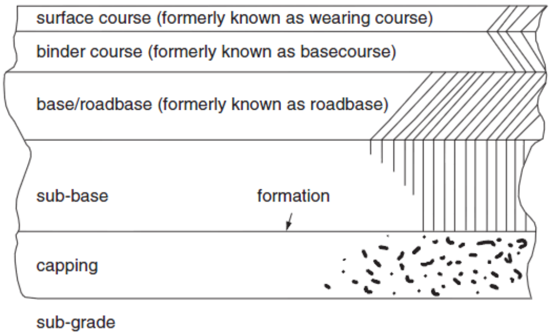


Figure 2-4 Typical road pavement structure Copson et al ,2004)

2.2.1 Road pavement design

The road pavement design is directly influenced by the expected traffic, expressed in number of vehicles or number of equivalent axles, during the adopted useful life of a road, normally 20 years. The quality of the material and the construction techniques should allow that no maintenance is required during the designed life. Although many factors such as geology of the region, environmental impact, materials availability or economic aspects could influence a road design, a list with the essential design variables can be summarised as follows (Roger, 2003):

- the strength of the subgrade
- the vehicles composition of traffic stream
- the volume of traffic predicted to use the highway over its design life
- layer thickness in the pavement
- the nature of material in each layer

The large number of parameters influencing the design makes necessary the introduction of efficient centralized procedures for the achievement of adequate standards. The American and European countries commonly follow the approaches suggested by the American Association of State Highway and Transportation Officials (AASHTO). The AASHTO road pavement design standards were developed on the base of the results of intensive tests performed in the late 1950s in the US to determine the effect of the road traffic on the road pavement behaviour (Bekele, 2011).

Different road structures are presented in the AASHTO guide for pavement design. The road structures are commonly subdivided in Macadam, Flexible, Rigid and Composite pavement. The denomination of these approaches depends on the material chosen for the surfacing which influences the organisation of the underneath compacted layers. It will be duty of the specialist the choice of the most suitable pavement design depending on traffic load, materials availability and economic conditions.

C&D materials can be used in all types of pavements mentioned before. Although the focus is on flexible pavements all of them are described for a complete context.

2.2.1.1 *Macadam*

The Macadam takes its name from by John Loudon McAdam, who developed this design approach in 1820. It is commonly considered as the direct evolution of the road structure implemented by the Romans. The Macadam pavement is constituted by a rigid foundation consisting of 25-30 cm diameter rock stones, surrounded by smaller aggregates (15-20 cm) bonded together by a cementing agent which is usually tar or asphalt (Cristiani, 2008). A simple sketch of the Macadam structure is shown in Figure 2-5.

This solution was so innovative and the application so intensive that roads in some states of the US are still called Macadam although other approaches are now used. This type of road construction cannot withstand heavy loads and therefore it is used in rural or low traffic level areas. Macadam pavements have the advantage of a simple installation, do not require complex technology and are very cheap.

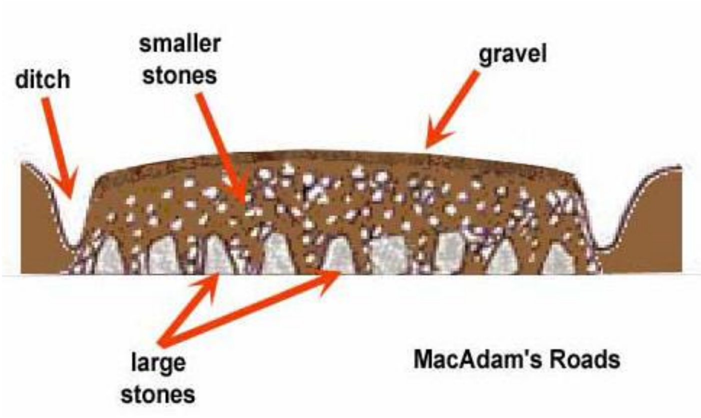


Figure 2-5 Macadam Pavement (Burchill et al, 2014)

2.2.1.2 *Flexible* pavement

The main characteristic of this pavement system is the ability of bending under applied loads. Flexible pavements are, in fact, characterized by an elastic-plastic-viscous behaviour due to the presence of bituminous treated materials in the main top layers. A flexible pavement structure consists of overlaid compacted layers of material. The entity of the compaction effort is maximum at the top of the embankment and decreases with depth.

Figure 2-6 shows the typical structure of a flexible pavement. It consists of four layers; from the top of a road embankment there are surface, binder, base and sub-base. Role of this structure is to properly spread the loads applied to the surface. Shear stress is mostly mitigated by surface, binder and base layers. The effect of the normal loads, however, is still appraised up to the unbound granular sub-base layer. The quality of the top two layers is critical for the correct behaviour of the whole structure as they control smoothness, rutting and shoving resistance and surface drainage of the road. Another important function of the binder is the top sealing of the lower layers of a road embankment.

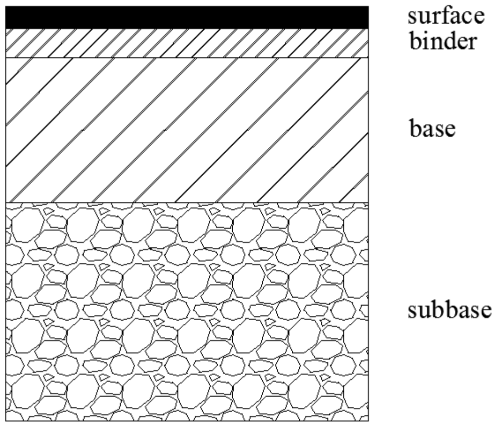


Figure 2-6 Flexible pavement section

The flexible pavement design needs also to take into account (Benedetto, 2005):

- The bearing capacity of the founding subgrade soil. It may withstand the weight of pavement layered system applied on it;
- The cyclic loads due to the traffic exceeding the fatigue limit. Their underestimation could allow the development of permanent deformations at the surface of the pavement;
- the service life of the pavement, expressed in years, which is the time after that a structure needs maintenance;
- The effect of the temperature which can induce critical state of stress in the surface layers that are cause of plastic deformations.

The flexible pavement structure has reasonable cost of construction and fast and simple maintenance procedures. The simplicity in restoring the road surface also facilitates the excavation procedures for the repair and upgrading of civil substructures (wires and pipes).

2.2.1.3 Rigid pavement

The rigid pavement, differently from the previous system, is characterised by rigid behaviour which allows minimal surface deformation and the application of a different stress distribution in the subgrade. These peculiarities are obtained by using special materials and construction techniques developed to increase the modulus of elasticity of the structure and especially of the surface. The element, which visually distinguishes this method from the others, is certainly the PCC (Portland Cement Concrete) reinforced slabs used to pave the road surface. The elastic behaviour of this concrete structure allows that all the deformations due to traffic, accidental loads or thermal gradients are completely restituted when the external sources of stress are removed.

The strain induced by thermal gradients between slab and beneath layer is the most critical for the structure soundness because it is cause of cracking. The occurrence of cracks in the slab is unacceptable since the localized reparation of the road surface is not possible and the only feasible option is the complete replacement of the damaged slab. For those reasons the rigid surface is not poured in only one slab but it is composed by a series of discrete slabs, providing expansion joint at the ends for reducing the probability of cracking.

The typical rigid structure provides that below the PCC other two layers are present, a stabilized base and an unbound sub-base course which is often omitted, as shown in Figure 2-7.

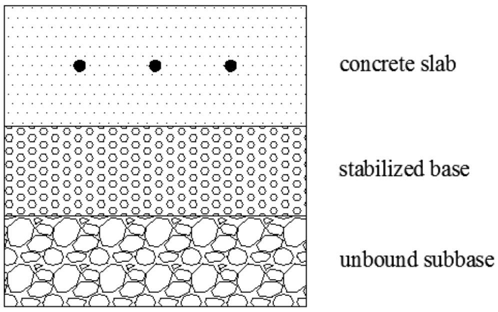


Figure 2-7 Rigid pavement section

The high shear resistance permits this type of pavement to reduce the layers thickness of a flexible pavement system. Consequence of the stiffness of the structure is also that the stress applied to the sub-grade soil is low enough to make this method particularly suitable in cases of low bearing capacity foundation soils (Lenz, 2011). The realization of these pavements requires substantial initial costs that, in the long term, are balanced by a long life and extreme durability which allows a significant reduction of maintenance costs.

2.2.1.4 Composite pavement

Another types of road structure are represented by composite pavements. The idea at the base of this design method is to combine the best qualities of rigid and flexible pavements. It is obtained by combining HMA or concrete road layers to build Rigid Composite Pavement or Flexible Composite Pavement (O'Flaherty, 2007) depending on the arrangement of these layers. Figure 2-8 shows two typical approaches with the main structures used.

Generally a flexible composite pavement has a bituminous Surface layer and a Base below in stabilized cement materials. The rigid composite pavement also has a thin bituminous surface but it is lying on concrete slabs.

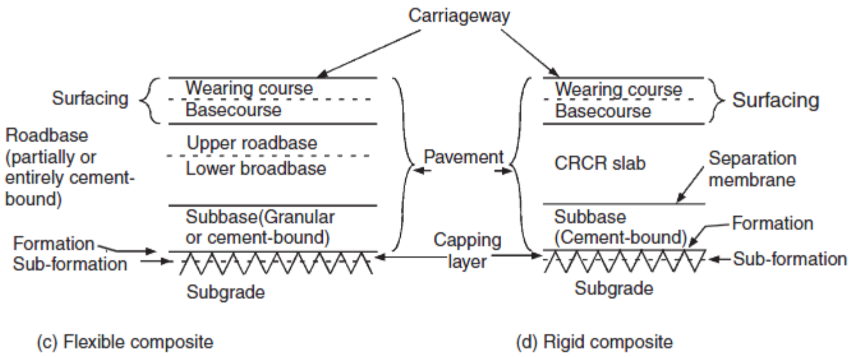


Figure 2-8 composite pavements (O􀂶Flaherty, 2007)

2.2.2 The South African Pavement design

In South Africa, despite the most common techniques of design for flexible pavements are accepted, the use of the Pavement Design Catalogue is strongly recommended (TRH4, 1996).

The first method for the design of concrete pavement is covered in Manual M10, which developed the AASHTO method refined and simplified for taking into account the conditions of the country. The manual was compared to overseas research and performance of local pavements resulting conservative and expensive therefore it was implemented in the cncPAVE.

Other labour intensive technologies, for instance segmented concrete block pavements, are suggested due to the economic organization of the country.

The South African approach was developed in 1970s with the support and approval of the Committee of State of Roads Authorities (CSRA). The guidelines commonly used in the country for the design, rehabilitation and maintenance of flexible, rigid and segment block road pavements. All the guidelines, rules and materials suggested for pavements construction are contained in these following documents:

- The Technical Recommendations for Highway (TRH), initially developed in 1985 and upgrade until 1996;

- Committee Of Land Transport Officials (COLTO) published the Standard Specifications for Road and Bridge Works for State Road Authorities in 1998, reviewed in 2008;
- Manual M10: Concrete Pavement Design and Construction published in 1995.
- The Urban Transport Guideline (UTG) published between 1986 and 1991

In 2013 the South African National Roads Agency (SANRAL), based on the concepts contained in these manuscripts, has developed the South African Pavement Engineering Manual (SAPEM), a new manual including the design, construction, maintenance and road rehabilitation. Within the manual, the approach suggested by AASHTO is also suggested although with some restrictions.

The typical organization of the layers in the most common pavement is presented in Figure 2-9. The names and layers distribution are very similar to those in use in other countries, the main difference is in the geotechnical characteristics of the materials used at different depth.

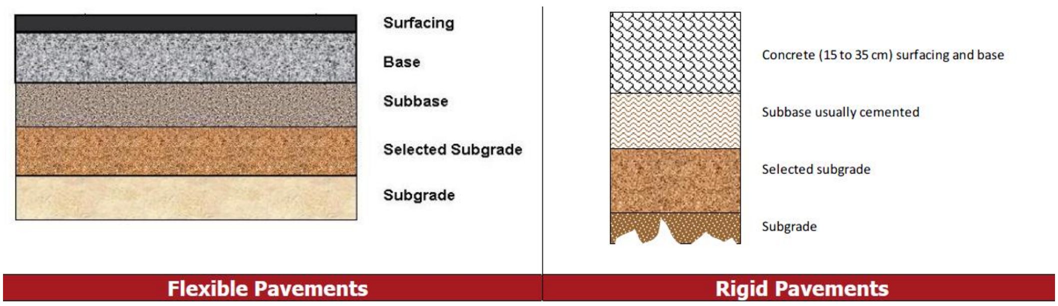


Figure 2-9 Typical South African Pavement Structures (South African National Road Agency, 2014)

2.2.2.1 Flexible pavement

In South Africa, despite the most common techniques of design for flexible pavements are accepted, the use of the Catalogue of typical pavement designs is recommended. The Design Catalogue, which is included in the Technical Recommendations for Highways Volume 4 (TRH4, 1996), subdivides the flexible pavements in 4 different types based on the characteristics of the road base used. The flexible pavement can be therefore classified in granular, bituminous, cemented or macadam. It is important to state that the application of the design catalogue should always be supported by analyses performed by means of other design methods

2.2.2.1.1 Granular base

The granular base is characterized by unbound granular layer, which ranges from well graded natural gravel to crushed stones or untreated gravels, with a thin surface layer stabilized with bitumen. The overall behaviour of this pavement is strongly influenced by the characteristics of the sub-base layer (TMH14).

Granular sub-base usually gives permanent plastic deformation due to densification and/or shear of the untreated material. Rutting and surface roughness are the main manifestation to demonstrate the deformations. It is noticed that materials used in this context should have, once compacted, an adequate bearing capacity especially in wet region (TMH14).

Cemented sub-base is generally used to increase the bearing capacity of the pavement and for this reason it is chosen for road with high density of traffic. Due to its stiffness the fatigue cracking is usually the failure mode, but unlikely it reflects to the surface.

A special material, classified as G1, is often used in high traffic road. All around the world it is tried to reproduced, even with different material compare to what South African guidelines suggests. This has unique properties and pavements made with it need a particular method of construction to ensure high density layers (South African National Road Agency, 2014). The characteristics of G1 material are so restrictive that not every material can be used as a granular base (Kleyn, 2012).

2.2.2.1.2 Cement base

The use of cement sub-base is suggested for high road categories. Due to the high modulus of Young a cement base is able to, in fact, easily absorb most of the traffic load applied at the surface. However, the transfer of high stresses to this layer, in combination with shrinkage and thermal action, can be obviously caused of cracking. A cemented base in flexible pavement is granular material stabilized with 5% of cement, which can lay on uncemented or cemented sub-base as well as the structure with granular base. In fact the addiction of small amount

A distinctive feature of these pavements is that the traffic stress is borne by the cemented layers and only a small part by the subgrade. The choice often depends on the materials available, traffic flow and the service life strategy.

The pavement composed by cement base on uncemented sub-base normally has a shallow structural balance which results sensitive to the moisture ingress in to the granular sub-base. This process, in fact, tends to weaken the structure when overloading.

Cemented sub-base instead a granular sub-base is normally favourite by road authorities for the ability of these pavements to inhibit active pumping, even though in terms of strength an uncemented sub-base, may suffice. This pavement consists of a deeper structure and generally it is less sensitive to overloading.

2.2.2.1.3 Hot Mix Asphalt base

The need for a durable surfacing material to tolerate the increasing heavy traffic has led to the introduction of the hot mix asphalt (HMA) in South Africa in the 1920s. Today, the application of the hot mix asphalt is also extended to road base structures as well as maintenance and rehabilitation.

Economic factors make the HMA convenient only in case of high traffic loads (3e06 E80s minimum). For this reason the resistance to fatigue and to plastic deformation is essential in the design of this kind of bases.

The AASHTO flexible pavement shows many similitudes with the HMA structure. The distinguishing base layer, 80 to 130 mm thick, consists of a mix of aggregate with a specific grading stabilized with bitumen. HMA base are supported by untreated or stabilised cemented sub-base. However, due to the high traffic load, the use of the latter sub-base is suggested.

The application of Large Asphalt Mixes for Bases (LAMBS) in the structure has similar behaviour with the normal mix but the structural properties are improved due to the use of bigger aggregates. The deriving stone skeleton structure helps to prevent deformations and fatigue cracking, recognized as the main failure mode of HMA base. The use of LAMBS reduces the production costs during the crushing and decreases the percentage of fine in the mix; however it is a relative new technology and it is not presented in the Catalogue.

2.2.2.1.4 South African Materials Codes

The choice of materials for road pavement design is based on various factors such as construction methodology, availability, experience, environmental and economic aspects. The use of a specific material directly influences the Life Cycle Strategy (LCS) of a road structure and allows predicting maintenance and rehabilitation actions. Different types of materials are suggested in the South African Pavement Design Catalogue and routinely employed in road construction.

Each material is classified accordingly to the specifications included in the TRH14 (1996) or COLTO (1998) and it is identified by an alphanumeric code (G1, G2, C1, C2, BEM, etc.). This classification permits to anticipate, through laboratory tests, their behaviours and strength characteristics. The elastic moduli and Mohr-Coulomb strength parameters suggested by Theyse et al. (1996) for natural road aggregates can be used for the design.

The following Table 2-5 shows codes and a brief description of the principal components of the most commonly used materials in road construction.

Table 2-5 Material used in South African Pavement Design (TRH14, 1985 and THH4, 1996)

Code	Material	
	surfacings and overlays	
AG	asphalt surfacing - gap graded	Surfacing
AC	asphalt surfacing - continuously graded	Surfacing
AS	asphalt surfacing - semi-gap-graded	Surfacing
AO	asphalt surfacing - open graded	Surfacing
S1	asphalt treatment - single seal	Surfacing
S2	asphalt treatment multiple seal	Surfacing
S3	sand seal	Surfacing
S4	cape seal	Surfacing
S5	slurry - fine grading	Surfacing
S6	slurry - coarse grading	Surfacing
S7	Slurry	Surfacing
S8	surface renewal	Surfacing
S9	surface renewal	Surfacing
	layered material (untreated)	
G1	graded crushed stone	Base
G2	graded crushed stone	Base
G3	graded crushed stone	Base
G4	natural gravel	Base
G5	natural gravel	sub-base
G6	natural gravel	sub-base
G7	gravel-soil	selected layer
G8	gravel-soil	selected layer, subgrade
G9	gravel-soil	selected layer, subgrade
G10	gravel-soil	Subgrade
WM1	waterbound macadam	Base
WM2	waterbound macadam	Base
DR	Dumprock	
	layered material (treated)	
C1	cemented crushed stone or gravel	base, sub-base
C2	cemented crushed stone or gravel	base, sub-base
C3	cemented natural gravel	base, sub-base
C4	cemented natural gravel	base, sub-base
BEM	bitumen emulsion – modified gravel	
BES	bitumen emulsion – stabilized gravel	
BC1	bitumen hot mix - continuously graded	Base
BC2	bitumen hot mix - continuously graded	Base
BC3	bitumen hot mix - continuously graded	Base
BS	bitumen hot mix semi-gap-graded	Base
TC	tar hot mix - continuously graded	Base
TS	tar hot mix - semi-gap-graded	Base
BT1	bituminous treated crushed stone	Base
BT2	bituminous treated natural gravel	Base
BT3	bituminous treated cohesionless sand	base, sub-base

PM	penetration macadam	Base
	concrete paving layer	
PCC	portland cement concrete	Surfacing
	gravelling wearing course	
GWC	gravelling wearing course	

Granular materials

Materials codified with the letter G are natural aggregates, produced by virgin materials, possibly extracted from nearby quarries. There are ten different types of granular materials ordered from the best quality material to the least. They are characterized by stress-dependent behaviour and can deform under repeated stresses but limited with a good design.

Macadams

Waterbound Macadams (WM) is particular granular materials consisting of single-sides aggregates mixed with fine during construction process for filling the voids. This kind of granular material has high water resistance and it is often used in wet region as base for pavement with heavy traffic.

Modified materials

These kinds of materials are treaded adding to natural gravels 2-3% of cement or bitumen as stabilizers. The purpose is to improve the workability and moisture sensitivity of a material for the use in surfacing or in stabilized base\sub-base layers.

Cemented materials

Cemented materials are codified with the letter C and divided in 4 types (C1, C2, C3 and C4). Their behaviours are initially elastic with limited tensile strength similar to the concrete and they tend to crack under repeated flexure or due to shrinkage during drying. Wide cracks can be avoided by the application of limit to the strength specification and reflection on the surface are prevented putting on top unbound layer.

Bituminous materials

Bituminous materials are numerous types and are used for surfacing, base and sub-base layers. Aggregates used for surfacing require high quality properties since the surface is exposed to rolling and static load and weathering. Materials from AG to AP have specific particle size distribution before mixing with bitumen. The seals (S1 to S9) are characterized by single-sized stone blended with natural sand and\or crushed sand.

Hot Mix Asphalt

Base and sub-base layers are prepared by Hot Mix Asphalt (HMA), called BC and BS, or by bitumen emulsion treated material, such as BEM and BES. They are a mix between bitumen and coarse aggregates that have different characteristics than those used for surfacing.

The listed materials are generally used in the past and often nowadays hence they are also called “traditional”. However there is an increased pressure to replace the traditional materials with alternative material due to depletion of natural source, conservation of power, awareness of environmental issues and its resulting regulations (South African National Road Agency, 2014). The South African laws and regulations have adjusted its manuals and its guidelines to the new point of view.

The SAPEM updated in 2014 offers new types of materials than those proposed in the TMH. The alternative materials that have been introduced are: recycled road pavement materials, construction and demolition waste, slags, fly ash, mine waste, other alternative materials.

The Table 2-5 should be reviewed for accommodating the alternative materials that also in South Africa should be used for a more sustainable pavement construction.

2.2.2.1.5 South African Pavement Design Catalogue

This present section reports the South African Catalogue for pavement designs. It suggests the correct pavement structure (the sub-base and foundations layout are also included) in accord to the bases chosen, road category and the predicted design equivalent traffic flow expressed in equivalent axles per direction. Drainage, compaction and shoulder requirements are also not included in the design catalogue but described in different sections of the same TRH4.

The road structures in the Catalogue are graphically represented and, for each layer, thickness and material used are closely attributed. The choice of materials for road pavement design was based on various factors such as construction methodology, availability, climatic and economic aspects. The use of a specific material directly influences the Life Cycle Strategy (LCS) of a road structure and allows predicting maintenance and rehabilitation actions.

Different types of materials are suggested in the South African Pavement Design Catalogue and routinely employed in road construction. Each material is classified accordingly to the specifications included in the TRH14 (1996) or COLTO (1998) and it is identified by an alphanumeric code (G1, G2, C1, C2, BEM, etc). This classification permits to anticipate, through laboratory tests, their behaviours and strength characteristics. The elastic moduli and Mohr-Coulomb strength parameters suggested by Theyse et al. (1996) for natural road aggregates can be used for the design.

The Catalogue and the material’s classifications are included in the Appendix A for consultation purposes.

2.2.2.2 Rigid pavement

The first method for the design of concrete pavement is covered in Manual M10, which developed the AASHTO method refined and simplified for taking into account the conditions of the country. The manual was compared to overseas research and performance of local pavements resulted conservative and expensive therefore it was implemented in the cncPAVE. When SAPEM was published it is also given updates of rigid pavement design.

Rigid pavements are often used in South Africa as well as overseas and there are three different types according to their crack control criteria:

- plain jointed concrete pavement (PJCP),
- continuously reinforced concrete pavement (CRCP)
- ultra-thin concrete pavement (UTCP).

Although the principles for a design of a rigid pavement are similar to those of a flexible pavement, the transition of strength and stiffness work in different ways. Because of its high elastic modulus, the rigid slab in concrete allows dissipating them rapidly from the top layer to the subgrade compare to the asphalt and granular layers. This represents an advantage especially when the subgrade has poor bearing capacity.

The first support consists of concrete slabs which have the same functions of thicker layers in a flexible pavement with granular or bituminous base. The characteristic of the slabs are essential to mitigate shrinkage cracking. The base is not present while the sub-base, a stabilized layer, plays an essential role to mitigate the erodibility.

2.2.2.3 Segmented concrete block pavements

A particular type of pavement is represented by segmented concrete blocks. This methodology has different uses than the construction of roads or highways. Three main design categories, depending on the purposes of the infrastructure, are associated to this approach:

- Architectural (A) for the construction of footpaths, slope protection, utility for commercial project (car parks, parks, shopping centres, stations, …), for domestic paving (driveways, swimming pool surrounds, townhouse and cluster homes) or for specialized applications (roof deck, farms, channels, …)
- Industrial (I), concrete block pavements provide good support and reasonable costs for industrial areas such as container deposits, heavy vehicle parking, factories and warehouse working areas, airport and harbour purposes.
- Roads (R) with this technique are driveways, parking areas, service stations, rural and urban.

Given the emphasis on the introduction of labour intensive construction techniques in the infrastructure sector, the segmented concrete block pavement system has proved to be a useful methodology in South Africa as well as in other developing countries. The success of the method is also due to the low costs and simplicity of construction and maintenance. The guidelines for the construction and the design of segmental concrete block pavements are included in the UTG volume 2 (1997) and in the new recommendation SAPEM (2014).

Figure 2-10 shows the typical structure of concrete paving blocks which consists of subgrade, sub-base, bedding and sand layer, concrete paving blocks and jointing sand, edge restraints and drainage.

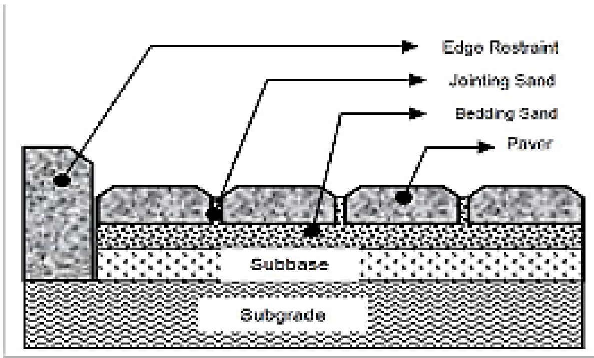


Figure 2-10 Segment block pavement

The subgrade is the ultimate natural support present on site and possibly should have suitable soil characteristics for withstanding the applied loads. A sub-base or more layers are required when heavy traffic is present or the subgrade is of a low strength to increase the bearing capacity. As for flexible pavement the sub-base can be stabilized with cement or, if unbound, it needs to be seal by spreading bitumen emulsion for preventing water filtering. The thin bedding sand layer, which lies on top of sub-base or subgrade, consists of permeable and non-erodible clean or crushed sand. It assures initial joints between the blocks pushing up some sand when concrete blocks are placed.

The segment concrete block pavements can be considered as concrete slabs with a continuous discontinuity. The behaviour falls somehow between flexible and rigid pavement, the blocks are stiffer than bituminous layer but less stiff than concrete layer. The applied loads are spread among the blocks by means of the sand placed in the interstices.

2.2.3 Geomechanical characteristics of granular materials

The choice of the correct granular material is essential in road construction as it ensures good performance and a long service life. Despite the multiplicity of aspects that influence the performance of engineering works, the extensive knowledge of the physic-chemical-mechanical properties of the involved materials is essential (Duggel, 2008). The geomechanical characteristics of an aggregate, as summarized in Table 2-6, define its present condition and nature (physical properties) but also the behaviour under solicitation (mechanical properties).

Table 2-6 Materials properties

properties	
physical	mechanical
density	strength
specific gravity	hardness
specific weight	plasticity
porosity	elasticity
void ratio,	
hygroscopicity	
water absorption	
durability	
permeability	
frost resistance	
chemical resistance	

Laboratory tests procedures for the investigation of each property are recommended by the Governments as well as guidelines for the interpretation of the results. The characteristics and the behaviours of a soil can be also determined by in situ testing or by back-analysis.

2.2.3.1 Soil Classification Systems

The role of geomechanical classifications is to summarize the observable characteristics of a soil in order to easily suggest appropriate uses or to predict its short and long term behaviour. The validity of these approaches is confirmed by several authors but in an advanced design stage a full geotechnical characterization would be preferred.

The most common soil classification systems are the universal Unified Soil Classification System (USCS) and the American Association of State Highway and Transportation Officials (AASHTO) Classification System.

The USCS consists of three main categories, gravel-sand-silt and clay, which are further divided into subgroups. For each of these groups a symbol composed by two letters is unambiguously associated to the material tested. The approach for the characterisation of a soil in accord to the UCSC approach is shown in Table 2-7.

Table 2-7 USCS

Major divisions			**Group symbol**	**Group name**
Coarse grained soils more than 50% retained on No.200 (0.075 mm) sieve	<u>gravel</u> > 50% of coarse fraction retained on No. 4 (4.75 mm) sieve	clean gravel <5% smaller than #200 Sieve	**GW**	well-graded gravel, fine to coarse gravel
			GP	poorly graded gravel
		gravel with >12% fines	**GM**	silty gravel
			GC	clayey gravel
	<u>sand</u> ≥ 50% of coarse fraction passes No.4 sieve	clean sand	**SW**	well-graded sand, fine to coarse sand
			SP	poorly graded sand
		sand with >12% fines	**SM**	silty sand
			SC	clayey sand
Fine grained soils more than 50% passes No.200 sieve	<u>silt and clay</u> liquid limit < 50	inorganic	**ML**	silt
			CL	clay of low plasticity, lean clay
		organic	**OL**	organic silt, organic clay
	<u>silt and clay</u> liquid limit ≥ 50	inorganic	**MH**	silt of high plasticity, elastic silt
			CH	clay of high plasticity, fat clay
		organic	**OH**	organic clay, organic silt
Highly organic soils			**Pt**	peat

The AASHTO soil classification system is a specifically used in road engineering environment. It was introduced for supporting the designer in the choice of the proper materials for each layer of a pavement. The seven groups that constitute this method are divided according to the particle size distribution and Atterberg limits of the fraction passing the 0.075mm sieve as shown in Table 2-8. The most suitable material for road construction purpose is classified as A1, which is defined by a 0.075mm passing smaller than 35%, and by a minor plasticity (PI<6 and LL=0).

Table 2-8 AASTHO Soil Classification System

General Classification	**Granular Materials (35% or less passing the 0.075 mm sieve)**							**Silt-Clay Materials (>35% passing the 0.075 mm sieve)**			
Group Classification	A-1		A-3	A-2				A-4	A-5	A-6	A-7
	A-1-a	A-1-b		A-2-4	A-2-5	A-2-6	A-2-7				A-7-5 A-7-6
Sieve Analysis, % passing											
2.00 mm (No. 10)	50 max	…	…	…	…	…	…	…	…	…	…
0.425 (No. 40)	30 max	50 max	51 min	…	…	…	…	…	…	…	…
0.075 (No. 200)	15 max	25 max	10 max	35 max	35 max	35 max	35 max	36 min	36 min	36 min	36 min
Characteristics of fraction passing 0.425 mm (No. 40)											
Liquid Limit	…		…	40 max	41 min	40 max	41 min	40 max	41 min	40 max	41 min
Plasticity Index	6 max		N.P.	10 max	10 max	11 min	11 min	10 max	10 max	11 min	11 min
Usual types of significant constituent materials	stone fragments, gravel and sand		fine sand	silty or clayey gravel and sand				silty soils		clayey soils	
General rating as a subgrade	excellent to good							fair to poor			

The South African classification for road construction material shows many similarities with the North American approach but it is more structured. In the American design method, in fact, some test is deferred to further phases, while it is considered necessary in the South African classification system. This approach allows the exact choice of the materials which will constitute the various aggregates layers of a flexible pavement as described in the Pavement Design Catalogue. Table 2-9 summarizes characteristics, parameters and properties for the classification of soil. Table 2-10, 2-11, 2-12 and 2-13 are an essential support for the use of Table 2-9.

Table 2-9 South African soil classification system

COLTO SPECIFICATION - MARCH 1998									
Review 27 November 2009									
PROPERTY	**G1**	**G2**	**G3**	**G4**	**G5**	**G6**	**G7**	**G8**	**G9**
DESRIPTION OF MATERIAL	Sound rock from an approved quarry, or clean, sound mine rock from mine dumps, or clean sound boulders	Sound rock, boulders or coarse gravel	-	Natural gravel, or natural gravel & boulders which may need crushing	Natural gravel, or natural gravel & boulders which may need crushing or crushed rock	Natural gravel, or natural gravel & boulders which may need crushing or crushed rock	Natural material (soil, sand or gravel)	Natural material (soil, sand or gravel)	Natural material (soil, sand or gravel)
ADDITIONAL FINES	Only fines crushed from the same sound parent rock may be added for grading correction provided that added fines shall have a LL not exceeding 25 and PI not exceeding 4	May contain up to 10% by mass of approved natural fines not necessarily obtained from parent rock. Added fines shall have a LL not exceeding 25 and PI not exceeding 6	May contain up to 15% by mass of approved natural fines not obtained from parent rock. Added fines shall have a LL not exceeding 25 and PI not exceeding 6	May contain approved additional fines not obtained from parent rock. Added fines shall have a liquid limit not exceeding 25 and a plasticity index not exceeding 6	May contain approved natural fines not obtained from parent rock.	May contain approved natural fines not obtained from parent rock.	-	-	-
NOMINAL MAXIMUM SIZE	37.5		37.5 - 26.5	Uncrushed 53mm : crushed 37.5 or 26.5mm	Uncrushed 63mm : crushed 53mm before compaction	Uncrushed : 2/3 compacted layer : crushed 63mm before compaction	Uncrushed : 2/3 compacted layer crushed material: 75mm	2/3 compacted layer	2/3 compacted layer
FLAKINESS INDEX	Flakiness Index, determined in accordance with TMH1 method B3, shall not exceed 35 on each of the -26.5+19mm fraction and the -19+13.2mm fraction				-	-	-	-	-
FRACTURED FACES	All faces shall be fractured faces	For crushed materials at least 50% by mass of the fractions retained on each standard sieve 4.75mm and larger shall have at least one fractured face.		Alluvial & colluvial gravels shall be crushed so that at least 50% by mass of the fractions retained on each standard sieve 4.75mm and larger shall have at least one fractured face	Alluvial & colluvial material shall be crushed so that at least 50% by mass of the fractions retained on 4.75mm shall have at least on fractured face				
GRADING	see next page	see next page	see next page	see next page	see next page				
GRADING MODULUS	-	-	-	-	2.5>GM>1.5	2.6 ≥ GM ≥ 1.2	2.7 ≥ GM ≥ 0.75	2.7 ≥ GM ≥ 0.75	2.7 ≥ GM ≥ 0.75
ATTERBERG LIMTS (-0.075mm FRACTION)	LL shall not exceed 25 PI shall not exceed 5 LS shall not exceed 2% In addition the arithmetic mean of the PI's for a lot (min 6 tests) shall not exceed 4	LL shall not exceed 25 PI shall not exceed 6 LS shall not exceed 3% In addition the arithmetic mean of the PI's for a lot (min 6 tests) shall not exceed 4.5	LL shall not exceed 25 PI shall not exceed 6 LS shall not exceed 3% In the case of calcrete the PI shall not exceed 8. (% passing 0.425mm sieve) LS ≤ 170	a) All materials except calcrete LL shall not exceed 25 PI shall not exceed 6 LS shall not exceed 3% b) Calcrete LL ≤ 25 PI ≤ 8 (% passing 0.425mm sieve) LS ≤ 170	a) All materials except calcrete LL shall not exceed 30 PI shall not exceed 10 LS shall not exceed 5% b) Calcrete LL ≤ 30 PI ≤ 15 LS ≤ 6 (% passing 0.425mm sieve) LS ≤ 320	PI shall not exceed 12 or a value equal to 2 times the GM plus 10, whichever is the higher value. LS shall not exceed 5%. In the case of calcrete the PI shall not exceed 15 provided the LS does not exceed 6% and (% passing 0.425mm sieve) LS ≤ 320	The PI shall not exceed 12 or a value equal to 3 times the GM plus 10, whichever is the higher value. In the case of calcrete the PI shall not exceed 17 provided that the LS does not exceed 7% and (% passing 0.425mm sieve) LS ≤ 320	The PI shall not exceed 12 or a value equal to 3 times the GM plus 10, whichever is the higher value. In the case of calcrete the PI shall not exceed 17 provided that the LS does not exceed 7%	The PI shall not exceed 12 or a value equal to 3 times the GM plus 10, whichever is the higher value. In the case of calcrete the PI shall not exceed 17 provided that the LS does not exceed 7%
ATTERBERG LIMTS (-0.075mm FRACTION)	The PI shall not exceed 12. If the PI exceeds 12 the material shall be chemically modified. After chemical modification the PI of the minus 0.075mm fraction shall not exceed 8.		If chemical modification is required, the PI of the -0.075mm fraction after modification shall not exceed 10	-	-	-	-	-	-
DURABILITY	The material shall comply with the requirements in columns 3, 4 and 5 of table 3602/2 (COLTO)			The material shall comply with the requirements in table 3402/3 (COLTO)	Mudrock shall have a wet 10% FACT value of not less than 90 kN, and a wet/dry Venter test class of I or II	Mudrock shall have a wet 10% FACT value of not less than 80 kN, and a wet/dry Venter test class of I or II	Mudrock shall have a wet 10% FACT value of not less than 60 kN, and a wet/dry Venter test class of I , II or III	Mudrock shall have a wet 10% FACT value of not less than 60 kN, and a wet/dry Venter test class of I , II or III	Mudrock shall have a wet 10% FACT value of not less than 60 kN, and a wet/dry Venter test class of I , II or III
SOLUBLE SALTS	See additional requirements (COLTO)			The material shall comply with the requirements in clause 3602 (COLTO)					
STRENGTH (CBR)	-	-	-	CBR at 98% of modified AASHTO	CBR at 95% of modified AASHTO	CBR at 95% of modified AASHTO denisty	CBR at 93% of modified AASHTO density	CBR at 93% of modified AASHTO density	CBR at 93% of modified AASHTO density

				denisty shall not be less than 80%	density shall not be less than 45%	shall not be less than 25%	shall be at least 15%	shall be at least 10%	shall be at least 7%
SWELL (MAXIMUM)				Swell at 100% modified AASHTO density shall not exceed 0.2% for all materials except calcrete for which the swell shall not exceed 0.5%	Swell at 100% modified AASHTO density shall not exceed 0.5%	Swell at 100% modified AASHTO density shall not exceed 1.0%	Swell at 100% modified AASHTO density shall not exceed 1.5%	Swell at 100% modified AASHTO density shall not exceed 1.5%	Swell at 100% modified AASHTO density shall not exceed 1.5%
COMPACTION REQUIREMENTS	Minimum 0f 88% of apparent relative density	Minimum of 85% of bulk relative denity	98% or 100% of modified AASHTO density (as specified)	98% or 100% (as specified) of modified AASHTO density for natural materials	The density requirements of the layer in which the material is used, shall be applicable. (See subclause 3402(b)(COLTO) In restricted areas the in situ dry density of gravel material shall comply wuth the requirements in the project specifications.				
Strength	10% fines aggregate crushing value (10% FACT), determined in accordance with TMH1 method B2, shall be not less than the appropriate value in table 3602/2, column 3. The Aggregate Crushed Value (ACV), determined in accordance with TMH1 method B1, shall not exceed the appropriate value in table 3602/3.								
COARSE SAND RATIO (SEE DEFINITION IN SUBCLAUSE 3602(c)(i)(5))	Shall not be less than 35% and shall not exceed 50% in respect of the target grading	Shall not be less than 35% and shall not exceed 50% in respect of the target grading	Shall not be less than 35% and shall not exceed 50% in respect of the target grading						

Table 2-10 Grading of crushed aggregates

GRADING OF GRADED CRUSHED STONE

		G1	G2	G3		G4			G5
	NOMINAL APERTURE SIZE OF SIEVE (mm)	PERCENTAGE PASSING SIEVE BY MASS	PERCENTAGE PASSING SIEVE BY MASS	PERCENTAGE PASSING SIEVE BY MASS		PERCENTAGE PASSING SIEVE BY MASS			
						CRUSHED		UNCRUSHED	
		37.5mm	37.5mm	37.5mm	26.5mm	37.5mm	26.5mm		
GRADING	53							100	The percentage by mass passing the 2.00mm sieve shall not be less than 20% nor more than 70%
	37.5	100	100	100		100		85-100	
	26.5	84-94	84-94	84-94	100	84-94	100	-	
	19	71-84	71-84	71-84	85-95	71-84	85-95	60-90	
	13.2	59-75	59-75	59-75	71-84	59-75	71-84	-	
	4.75	36-53	36-53	36-53	42-60	36-53	42-60	30-65	
	2	23-40	23-40	23-40	27-45	23-40	27-45	20-50	
	0.425	11-24	11-24	11-24	13-27	11-24	13-27	10-30	
	0.075	4-12	4-12	4-12	5-12	4-12	5-12	5-15	

Table 2-11 Maximum values accepted for 10% FACT

10% FINES AGGREGATE CRUSHING VALUES (Table 3602/2)				
Rock Type	Matrix	Dry (min.)	Wet (min.)	Wet / Dry (min.)
Araceneous rocks	non-siliceous cementing material	140 kN		75%
	siliceous cementing material	110 kN		75%
Diamicites (tilites)		200 kN		70%
Argillaneous rocks		180 kN	125 kN	-
Other rock types		110 kN		75%

Table 2-12 Maximum values accepted for ACV

AGGREGATE CRUSHING VALUE (Table 3602/3)	
Rock Type	ACV (max)
Araceneous rocks: without siliceous cementing matrix	27%
Araceneous rocks: with siliceous cementing matrix	29%
Diamicites (tilites)	21%
Argillaneous rocks	24%

Other rock types	29%

Table 2-13 Maximum values accepted for DMI

DURABILITY REQUIREMENTS FOR G4 MATERIAL (Table 3402/3)			
GROUP	MEMBER OF GROUP	DURABILITY MILL INDEX (MAX)	% PASSING 0.425mm SIEVE AFTER DURABILITY MILL TEST (MAX)
basic crystalline rock	basalt, dolerite, gabbro	125	35
acid crustaline rock	gneiss, granite	420	35
high silica rock	chert, hornfels, quarzite	420 (clay mineral kaolin)	35
Sandstone	arkose, conglomerate, sandstone, silistone	125	35 (increase from original not more than 15%)
Mudrock	mudrock, phylitte, shale, etc.	125	35
carbonate rock	dolemite, limestone, marble	not applicable	not applicable
Diamictities	greywacke, tillite	125	35
pedogenic material	calcrete, ferricrete, silcrete	480	40

A new classification or an adaptation of an old one for a proper use of C&D materials in road construction should be done.

Some researchers have suggested few other classifications for the reuse of C&D in road construction according to its composition. Mulheron (1991) recognized four main groups (excluding asphalt road planings).

- **Clean crushed concrete**: Crushed and graded concrete containing less than 5% of brick of other stony material.
- **Clean crushed brick**: Crushed and graded brick containing less than 5% of other materials such as concrete or natural stone.
- **Clean demolition debris**: Crushed and graded concrete and brick.
- **Crushed demolition debris**: Mixed crushed concrete and brick that has been screened and sorted to remove excess contamination, but still contains a proportion of wood, glass or other impurities

In the 1998 the BRE Digest proposed three classes of recycled aggregated concrete (RCA) based on the amount contained in the examined amount of material, as shown in Table 2-14

Table 2-14 Clsses of RCA

Class	Origin	Brick Content (%)
RCA I	Brickwork	Up to 100
RCA II	Concrete	0 – 10
RCA III	Concrete & brick	0 – 50

Another classification has been suggested by Sweere (1991) who has defined crushed concrete as shown in Table 2-15.

Table 2-15 Composition of crushed concrete

Component	Description
Main components	At least 80% by mass of crushed gravel or crushed aggregate concrete. At most 10% by mass of other broken stony material, the particles of which shall have a particle density of at least 2 100 kg/m3.
Additional elements	At most 10% by mass of all other materials, such as crushed stone or broken stony material. Asphalt shall not exceed 5% by mass.
Impurities	Maximum 1% non-stony material, i.e., plastic, plaster and rubber acceptable. Maximum 0.1% decomposable organic matter such as wood and vegetable remains.

Table 2-16 gathered the potential uses for C&D materials divided according to what it contains.

Table 2-16 Potential uses of Construction and Demolition Waste

Product	Potential Use
Crushed concrete	May be used as a substitute for natural aggregates for most purposes. Concrete derived from the demolition of buildings is likely to contain reinforcement, making it difficult to crush. It is also likely to be contaminated with other building waste materials.
Recycled crushed cement bound subbase and base	May be crushed or milled to produce granular materials meeting the requirements for a subbase. May also be restabilized with cement or bitumen to produce a stabilized material.
Crushed brick	Where bricks are available in quantity but are unsuitable for re-use, they may be crushed to produce granular materials meeting the requirements for a subbase. Contamination from gypsum plaster could result in crushed bricks having unacceptably high sulphate content. Some brick types have soluble sulphate contents high enough to be deleterious.
Crushed demolition debris (other than concrete and masonry)	May be used as general fill. Rubble containing timber should be avoided because, when it rots, cavities remain in the fill.

The classifications which have been described previously are not sufficient for an accurate assessment of C&D material for the use in road construction. The next study should meet all the results obtained so far and make a new suitable classification for this material or, in South African case, accommodate them in the existing classification. The parameters for evaluation are the same for natural material such as grading, Atterberg limits and maximum dry density, California bearing ratio etc.as in South African case. Particular attention has to be dedicated to the water content and durability tests.

2.3 Monitoring and testing of roads

2.3.1 The role of monitoring

The role of monitoring is indispensable in all engineering fields for the assessment of the real characteristics and conditions of a material, product or construction. Through this the behaviour of the object under test is constantly analysed. The study of this trend allows observing irregular performance, which could be caused by errors during the design or construction (Della Rizza, 2010), proving the new technologies and estimating useful life. Moreover the monitoring of the specific sections of civil work may describe the "decay curve" and then plan rational and economic maintenance. Laboratory tests are in fact not always sufficient to analyze adequately materials that are using in engineering applications. For instance, the specifications for granular materials are studied only for specific behaviours and cannot represent all the particle size distributions. In addition to this, for the difficulties involved in the representation of the stresses applied to the particles of soil, the geo-mechanical laboratory test simplify the real force involve (Vorster and Grabe, 2013). As well as the environmental conditions the observation of the real behaviour of a material will lead more comprehensive analysis.

2.3.2 Monitoring Methods

Nowadays there are a lot of monitoring techniques, which analyse totally or partially the behaviour of a work or a single part of it. The monitoring methods are divided into two big categories.

The first one includes the classic methods, which provide details of a structure by means of laboratory tests on sample taken from the observed work or by in-situ tests. These approaches are usually called destructive methods because cause the damage of the structure.

Nowadays the use of non-destructive methods is preferred. The main advantage of non-destructive testing (NDT) is that the sample stays in its place; it will not be destroyed (Dalla Rizza, 2010) and wasted saving money and protecting the environment (Graveen, 2001). The process is less laborious and cheaper than classical methods; therefore larger number of tests can be done resulting optimal for contractors and clients. If regularly used, NDT helps to prevent defects and reduce the possibility of incidents. The construction or design process can be improved maintaining high standards required from industry (Dalla Rizza, 2010).

According to Cartz (1995) and Losert (2009) the main methods used in NDT machine can be summarized in seven groups, shown in the following list:

- visual inspection,
- ultrasonic,
- radiographic,

- magnetic-particle,
- liquid penetrant,
- eddy-current testing,
- low coherence interferometry.

In road field, NDT prevent the damage of some part due to coring or the dismantling of the entire road section (Rowe et al, 1984), also reduce problems to the traffic stream for a long period. The sampling is often problematic or impossible due to the location and to environmental surroundings.

The monitoring of a road section has three main aspects surface, structure and environmental assessment (Stryk and Pospil, 2009). Riding quality, evenness, skid resistance, macrotexture and percentage of defects are commonly parameters to evaluate the condition of the surface. The structure assessment considers factors such as bearing capacity or cracking index, while noise and air pollution describe the environmental state of the road.

The most used methods are those that evaluate the stability of the structure during its construction or before opening the road to the public and they could be defined as in situ tests. Nowadays embedded sensors within the pavement are often used for research purposes which give the advantage of constant monitoring.

2.3.2.1 In situ tests

Nuclear gauge, Dynamic Cone Penetrometer (DCP), Falling Weigh Deflectometer (FWD), Seismic Pavement Analyser, Ground Penetrating Radar (GPR) are commonly employed.

2.3.2.1.1 Nuclear Density Gauge

Nuclear Density Gauge measures the in-situ density and moisture content of the asphalt or granular material layer placing the device on the surface or digging a little hole for introducing the rod. This method takes few minutes and immediately gives results. The nuclear gauge method is in contrast to the sand replacement method, which requires the excavation of a hole of specified dimensions, which depends on the equipment and specifications, for instance 150 mm diameter and 150 mm depth, then the gathered data will be processed.

Figure 2-11 shows schematically the device operation. The gauge realises gamma radiation, which are present in the retractable rod, in various directions which interact with the electrons of the pavement. The density of the material is calculated by the percentage of the reflected rays which return to the device.

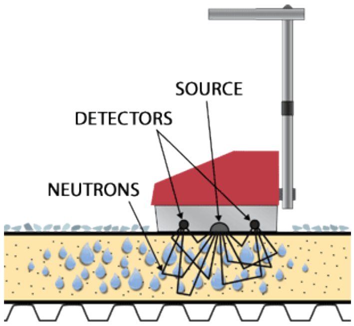


Figure 2-11 Nuclear Gauge (http://www.iranalyzers.com/nuclearroof.htm)

2.3.2.1.2 Dynamic Cone Penetrometer (DCP)

The DCP measures the in-situ strength of subgrade, unbound granular layer or weakly stabilized materials. This instrument consists of a long bar with a moving weight and a metal cone at the end as shown in Figure 2-12. The test is carried out by placing the cone on the layer face and a weight of 8 kg dropped with specific number of blows, typically 5. The penetration of the bar determines the result; subgrades generally have a penetration of 800 mm. This instrument is not used in other material such as asphalt layer or strongly cemented layer since no penetration is observed (South African National Road Agency. 2014).

The bearing capacity of the structure will be not altered and for this reason this method is considered non-destructive.

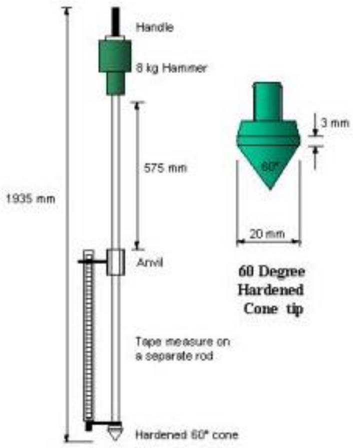


Figure 2-12 Dynamic Cone Penetometer

2.3.2.1.3 Seismic Pavement Analyser (SPA)

The Seismic Pavement Analyser and its portable version (PSPA) evaluate the general structural conditions of the pavement (Yuan et al, 1999). For instance, the identification of change in stiffness provides for the formation fatigue cracking that generates structural distress in flexible pavement (Jurado et al, 2012) or calculate parameters such as isotropy, variability and repeatability of seismic moduli for pavement layers (Steyn and Sadzik, 2007).

The device, shows in Figure 2-13, emanates vibrations at different frequency through different pneumatic hammers and a set of sensors, located at fixed distance, analyse the response of the pavement.

Figure 2-13 (Jurado et al, 2013)

2.3.2.1.4 *Falling Weight Deflectometer (FWD)*

Another non-destructive method frequently used is the FWD for wheel load simulation by means of the measurement of the deflection bowl. This test allows the calculation of the elastic moduli of the layers of any type of pavement with the backcalculation and layer thickness (Edward and Mason, 2011).

The device is mounted or carried by a vehicle as a trailer (FHWA, 2006). Figure 2-14 shows the equipment operation: a weight is dropped on the pavement surface and a series of geophones measure the deflection from point 0 to 1800mm distance.

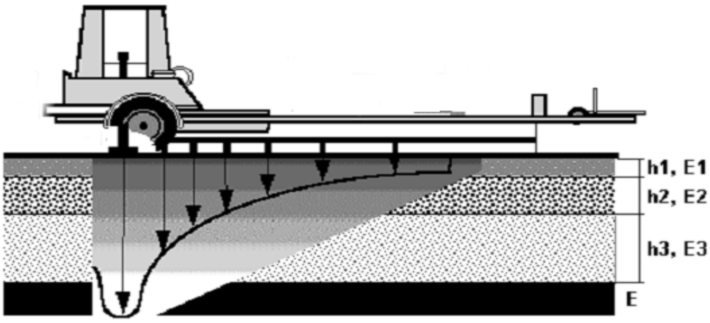


Figure 2-14 Falling Weight Deflectometer (Brandley,)

2.3.2.1.5 *Benkelmann Deflectometer*

The use of Benkelmann beam is another method to determine rebound deflection on the surface and a curvature function of a flexible (Marradi and Marvogli, 2007) or rigid pavement under a standard wheel load (static load). Characteristic such as stiffness of a pavement layer and resilient modulus of the subgrade are determined by backcalculation methods. The

Benkelmann beam consists of a device which has been installed between rear wheels of a truck and the collection data occurs during its passage.

2.3.2.1.6 Ground Penetrating Radar (GPR)

The estimation of the thickness of each layer in a pavement can be also evaluated by the GPR eliminating the traditional methods such as coring. Figure 2-15 shows standard equipment assembled in a vehicle eliminating the need to close a lane for the investigation (Saarenketo and Scullion, 2000). It scans the pavement by means of radar pulses which produce variation in the signal and reflected to an antenna.

Figure 2-15 Ground Penetrating Radar (VNA)

2.3.2.1.7 Light drop-weight deflectometer

The estimation of the bearing capacity and the compaction quality of a soil could be determined by light weight deflectometer. It is a portable instrument which calculates compaction after some weight drops. The test can be reproduced easily at a short distance from another point giving the idea of the uniformity of the structure calculated by the modulus E_{vd} (Coni et al., 2012).

2.3.2.2 Pavement instrumentation

Recently the use of embedded instruments in real scale soil structures has seen a relevant increase in the scientific literature for studying its reaction to the application of external load, verifying durability characteristics or the long term effect of the environment.

In 1945 the first experimental embankment monitored by sensors was constructed. Since then many others instrumented pavements have been studied especially for research purposes with more developed instruments (Larsson et al., 1997).

The instruments are typically installed during the construction of embankments for minimise the disturbance effect of a successive installation. They are usually connected by cables (Al Qadi et al., 2010), sometimes via wireless (Steyn, 2011) to a fixed or portable data acquisition system which is able to convert the signal coming from them in measurements.

The monitoring of some physical characteristics of a pavement could give a trend of a long-term global behaviour, verify malfunctioning and then planning maintenance and prevent failure.

In the road construction is a good practice monitoring the changing during the time of pressures, strains and moisture content.

The main advantage of these devices is that they are able to offer a constant monitoring of the structure under exam while its rest and under stress, or when the weather conditions change. Various studies have been done for assessing the interaction between vehicles and pavement (Steyn, 2011) or the suitability of new materials in road pavement (Coni et al., 2012).

2.3.2.2.1 LVDTs

The displacements within a compacted material under stress are generally less than a millimetre. The difficulty of recording such movements is overcome through Linear Variable Differential Transformers (LVDTs) is suggested. These devices, shown in Figure 2-16, transform infinitesimal mechanical movements of a probe in a proportionate electrical signal, which facilitate the collection of accurate data. The use of LVDTs for pavement monitoring allow verifying the effect of the traffic speed at various layers (Al Qadi, 2004) or how much the degree of compaction level and the nature of material used affect the deformation in lower layers (Coni et al, 2012).

Figure 2-16 Linear Variable Differential Transformers

2.3.2.2.2 Pressure Cells

Vertical stress applied on the surface of a pavement could be measured at a different depth by means of earth pressure cells. Figure 2-17 shows how they are constituted by a circular plate filled with oil and connected to an electric pressure transducer by a tube of steel. These instruments are generally used into embankments or dams, underneath the foundations, tanks and bridge piers. In particular the stress in road layers is measured under vehicles passing Al Qadi et al (2003) have observed that tyre pressure is influential on stress and strain under 150 mm.

Figure 2-17 Earth pressure cell

2.3.2.2.3 Strain gauges

A particular interest is the study of long term fatigue performance of flexible pavements for the presence of Hot Mix Asphalt (HMA) and its vertical compressive stress which are affected significantly by the temperature. Speeds affect horizontal transversal strain under HMA, but not compressive vertical stress in layers (Al Qadi et al 2003). Strain gauges are devices used in these cases. They consist of conducting materials where the resistance changes according to the strain.

2.3.2.2.4 Thermocouples and TDRs

The behaviour of the pavement is also a function of the environmental conditions, which are assessed thermocouples or Time Domain Deflectometer (TDR) (Coni et al 2012). Thermocouples are made by two different metals that joined at one end as shown in Figure 2-18. A voltage, produced when the junction is cooled or heated, is related to the temperature. Figure 2-19 shows TDRs which are devices for measuring moisture content in soils. Different kinds of these instruments are present in the market but they use the same principle by passing electric current into the ground in between the two polarities and assessing their signals. They have been often used in geotechnical field for studying slope stability (Dowding and O'Connor, 2000), agriculture for irrigation scheduling, along telecommunication lines for measuring corrosion and other disciplines.

Figure 2-18 Thermocouples

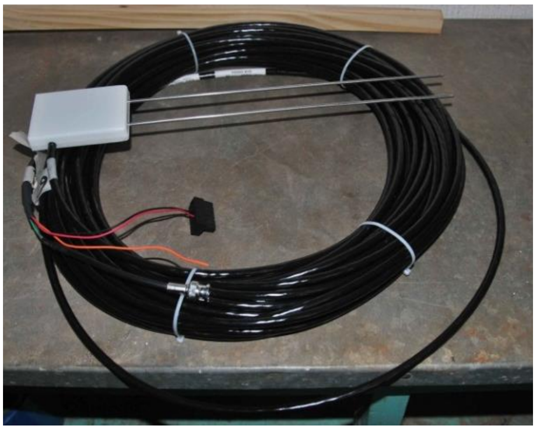


Figure 2-19 Time Domain Deflectometer

References

[1] Almut, R; Fischer, C; Werge, (2008) M. EU as a Recycling Society. Present recycling levels of Municipal Waste and Construction & Demolition Waste in the EU. European Topic Centre on Sustainable Consumption and Production (ETC/SCP). Denmark

[2] Angulo S.C., Mueller A. (2009) Determination of construction and demolition recycled aggregates composition, in considering their heterogeneity. Materials and Structures 42:739–748

[3] Annunziata F, Coni M, Maltinti F, Pinna F, Portas S, (2004) Progettazione stradale integrata. Zanichelli editore S.p.a. Bologna, prima edizione-giugno.

[4] Arslan H., Coşgun N., Salgın B. (2012) Construction and Demolition Waste Management in Turkey, Chapter 14 of Waste Management – An Integrated Vision, Luis Fernando Marmolejo Rebellon, InTech

[5] Bailey, L. H., and Wilhelm Miller. Cyclopaedia of American Horticulture, Comprising Suggestions for Cultivation of Horticultural Plants, Descriptions of the Species of Fruits, Vegetables, Flowers, and Ornamental Plants Sold in the United States and Canada, Together with Geographical and Biographical Sketches. New York [etc.]: The Macmillan Co, 1900

[6] Bairagi NK, Ravande K, Pareek VK. (1993) Behaviour of concrete with different proportions of natural and recycled aggregates, Resour. Conserv. Recycl., 9 (3), pp. 109–126

[7] Barbudo A., Agrela F., Ayuso J, Jiménez JR, Poon CS. (2012) Statistical analysis of recycled aggregates derived from different sources for sub-base applications. Construction and Building Materials, 28

[8] Bekele A., (2011) Implementation of the AASHTO Pavement Design Procedures into MULTI-PAVE, Master Degree Project, Division of Highway and Railway Engineering, Department of Civil and Architectural Engineering, Royal Institute of Technology, SE-100 44 Stockholm

[9] Benedetto A. (2005) Lecture Notes: La sovrastruttura stradalele pavimentazioni – Principi, Università di Roma3

[10] Brito de J, Pereira A.S., Correia J.R., (2005) Mechanical behaviour of non-structural concrete made with recycled ceramic aggregates, Cement and Concrete Composites Volume 27, Issue 4

[11] Burchill S., Hughes N., Gale R., Price P. and Woodall K., (2014) The Development of roads http://www.saburchill.com/history/chapters/IR/024.html

[12] Carmody J., Strong R. and Jacobson R. (2011) The Minnesota Site and Building Carbon Calculator, (Prepared by the Center for Sustainable Building Research 2/24/2011 Page 28 - Regents of the University of Minnesota, Twin Cities Campus, College of Design)

[13] Cartz, L. (1995). Nondestructive Testing. A S M International. ISBN 978-0-87170-517-4.

[14] Casagrande A. (1948) Classification and Identification of Soils. Transactions, ASCE, 113: 901–930

[15] Committee of Land Transport Officials (COLTO) (1998) Standard specification for road and bridge works, SAICE

[16] Committee of State Road Authorities, TRH04 (1996) Technical Recommendations for Highways - Structural design of flexible pavements for interurban or rural road

[17] Committee of State Road Authorities, TRH14 (1985) Technical Recommendations for Highways – Guidelines for road construction materials. Department of Transport, Pretoria

[18] Committee of State Road Authorities, TRH19: Technical Recommendations for Highways

[19] Coni, M., Rombi, J., Zedda, V., Portas, S. and Pistis S. (2012) Monitoring the Performances in Real Working Conditions of C&D Waste Materials in Road Construction using Embedded Instruments. PEAT Journal 13: 11-23.

[20] Copson M., Kendrick P., Beresford S., McCormick P. (2004) Roadwork: Theory and Practice, Elsevier, Oxford

[21] Corbishley M. (1986) The Roman World,Warwick Press, Kingfisher (editor)

[22] Costa, N. A. F., (2003). A reciclagem do resíduo de construção e demolição: Uma aplicação da análise multivariada. *Tese (Doutorado)* Universidade Federal de Santa Catarina, Florianópolis

[23] Cristiani L. (2008) Lecture Notes, Sovrastrutture- Pavimentazioni Stradali, Università di Pavia

[24] Deutsche Institut fur Normung (2002) Aggregate for mortar and concrete – part 100: recycled aggregates.

[25] Dolan, P.J., Lampo, R.G. and Dearborn, J.C. (1999). Concepts for reuse and recycling of construction and demolition waste. USA Construction Engineering Research Laboratories Technical Report 99/58

[26] Dong S, Kurt W. T., Wu Y. (2001)Municipal solid waste management in China: using commercial management to solve a growing problem, Utilities Policy 10

[27] Duggal S.K. (2003) Building Materials, New Age International Publishers, Third Edition, New Delhi

[28] Edward L. and Mason Q. (2011) Evaluation of Nondestructive Methods for Determining Pavement Thickness, final report prepared for Headquarters, Air Force Civil Engineer Support Agency

[29] European Environmental Agency (EEA) (2002) Review of Selected Waste Streams. Technical Report N.69, European Environmental Agency, Copenhagen, Denmark.

[30] European Commission (2008) European Union Waste Framework Directive, 2008/98/EC

[31] European Commission (2002) European Waste Catalogue and hazardous Waste List, http://www.nwcpo.ie/forms/EWC_code_book.pdf and http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=CONSLEG:2000D0532:20020101:EN:PDF

[32] Fernandez, N.P. (2008) The Influence of Construction Materials on Life Cycle Energy Use and Carbon Dioxide Emissions of Medium Size Commercial Buildings, M. Sc. thesis. Victoria University of Wellington.

[33] Franklin Associates (1998) Characterization of building-related construction and demolition debris in the United States. Prepared for The U.S. Environmental Protection Agency Municipal and Industrial Solid Waste Division Office of Solid Waste, Report No. EPA530-R-98-010

[34] Geoghegan Michael (2010) speech http://www.china-briefing.com/news/wp-content/uploads/2010/04/HSBC-Speech-27Apr10.pdf

[35] Gomes M. and Brito de J. (2009) Structural concrete with incorporation of coarse recycled concrete and ceramic aggregates: durability performance, Materials and Structures (2009) 42:663–675

[36] Hendricks and Jassen, (2001) Reuse of Construction and Demolition Waste in Netherlands for road construction, Heron, Vol. 46, No2

[37] Huang WL, Lin DH, Chang NB, Lin KS, (2002) Recycling of construction and demolition waste via a mechanical sorting process. Resources, Conservation and Recycling 37: 22-37

[38] Hugenschmidt, J. (2010) Geophysics and non destructive testing for transport infrastructure, with special emphasis on ground penetrating radar. Doctor of Sciences Thesis, ETH Zürich, Switzerland.

[39] Interactive Planning Workshop for Johannesburg. Greater Johannesburg Metropolitan Council. Johannesburg, South Africa. 27–30 September 2000. Web. 8 October 2011. http://web.mit.edu/urbanupgrading

[40] Inyang H. (2003) Framework for Recycling of Wastes in Construction. Journal of Environmental Engineering 129: 887–898

[41] Jurado M., Gibson N., Celaya M., Nazarian S. (2012) Evaluation of Asphalt Damage and Cracking Development with Seismic Pavement Analyzer, Transportation Research Record: Journal of the Transportation Research Board, No. 2304, Transportation Research Board of the National Academies, Washington, D.C.

[42] Kourmpanis B., Papadopoulos A, Moustakas K., Stylianou M., Haralambous KL, Loizidou M. (2008) Preliminary study for the management of construction and demolition waste. Waste Management & Research 26: 267–275

[43] Larsson R, Bengtsson PE, Eriksson L. (1997) Prediction of settlements of embankments on soft, fine-grained soils. Swedish Geotechnical Institute. Linkoping

[44] Leite, M. B., (2001). Avaliação de propriedades mecânicas de concretos produzidos com agregados reciclados de resíduos de construção e demolição. Tese (Doutorado em Engenharia Civil) Universidade Federal do Rio Grande do Sul, Porto Alegre.

[45] Losert, R. (2009). "Solution for NDT Inspection". NDT Magazine

[46] Macozoma, S.D. (2006) Developing a self-sustaining secondary construction materials market in South Africa. A dissertation submitted to the University of the Witwatersrand, to fulfill the requirements for the degree of Master of Science in Engineering. Faculty of Engineering and the Built Environment. Johannesburg, South Africa. University of the Witswatersrand

[47] Maczulak A (2010) Waste Treatment – Reducing Global Waste, Green Technology, New York

[48] Manual M10: Concrete Pavement Design and Construction South Africa. Chief Directorate National Roads Director General, Transport, Chief Directorate, Roads, Department of Transport, Pretoria, 1995

[49] Marradi A and Marvogli M, (2007) Falling Weight Defelctometer measurements for evaluation of bearing capacity of granular unbound layers, 4th International SIIV Congress – Palermo (Italy), 12-14 September

[50] Moore E. (2012) Civets, Brics and the Next 11, Financial Times 8th June

[51] Morse A. A. and Green R.L. (2009) Pavement and design Rehabilitation, Chapter 3 of Highway Engineering Handbook, 2nd ed., Roger L. Brockerbrough and Kenneth J. Boedecker, Eds., New York: McGraw-Hill

[52] O'Flaherty C. A. (2007) Highways: The location, design, construction and maintenance of road pavements, Butterworth Heinemann, 4th edition, Oxford

[53] OECD (2004-02-26). "Glossary of Statistical Terms". Retrieved 2007-07-17

[54] Olivari M. (1994) Elementi di teoria e tecnica della circolazione stradale, F. Angeli, Milano

[55] Organisation for Economic Co-operation and Development (2002) OECD.org. Retrieved 2013-05-30. http://www.oecd.org/general/organisationforeuropeaneconomicco-operation.htm

[56] Paschoalin, R. F., De Carvalho, A. C. and Barroso Castanon J. A. (2012) Construction and Suitable Development of Recycle and Demolition Waste. 28th Conference, Opportunities, Limits & Needs Towards an environmentally responsible architecture Lima, Perú

[57] Paschoalin, R. F., De Carvalho, A. C. and Barroso Castanon J. A. (2012) Construction and Suitable Development of Recycle and Demolition Waste. 28th Conference, Opportunities, Limits & Needs Towards an environmentally responsible architecture Lima, Perú

[58] Peterson C. and Godin J. (2004) Clean Development Mechanism and Development of a Methodology for the Recycling of Municipal Solid Waste, http://www.iswa.org/uploads/tx_iswaknowledgebase/4-286.pdf

[59] PINTO, T. P., (1999). Metodologia para a gestão diferenciada de resíduos sólidos da construção urbana. *Tese (Doutorado)* - Escola Politécnica, Universidade de São Paulo. São Paulo

[60] Poon C.S., Ann T.W. Yu, L.H. Ng (2001) On-site sorting of construction and demolition waste in Hong Kong, Resources, Conservation and Recycling, 32 (2001) 157–172

[61] Poon C.S. (2007) Management of construction and demolition waste. Waste Management 27 (2)

[62] Probati Eugenio (2008) Lecture Notes: Sovrastrutture - pavimentazioni stradali

[63] Roger M. (2003) Highway Engineering, Blackwell Publishing Ltd, Oxford

[64] Rowe R.K, MacLean A M., D, Barsvary. K. (1984) The observed behaviour of a geotextile-reinforced embankment constructed on peat, Canadian Geotechnical Journal, Vol. 21, Issue 2

[65] Saarenketo T and Scullion T. (2000), Road evaluation with ground penetrating radar, Journal of Applied Geophysics, Volume 43, Issues 2–4

[66] Saez Paola Villoria, Merino Mercedes del Río, Porras-Amores César, Managing construction and demolition (C&D) waste – a European perspective. (2011) International Conference on Petroleum and Sustainable Development IPCBEE vol. 26 IACSIT Press, Singapore

[67] Shire of Wyndham East Kimberly (2006). "Guidelines for rural road design and construction technical specifications" (PDF). Western Australia (The Last Frontier). Archived from the original on 2007-07-10. Retrieved 2007-04-24.

[68] Shrivastava, Sandeep, M.E. Rinker, (2009) http://www.irb.fraunhofer.de/CIBlibrary/search-quick-result-list.jsp?A&idSuche=CIB+DC14286

[69] South African National Road Agency. 2014. South African Pavement Engineering Manual (SAPEM). Republic of South Africa 2° edition

[70] Steyn W. JvdM and Sadzik E (2007) Application of the Portable pavement Seismic Analyser (PSPA) for pavement analysis, Proceedings of the 26th Southern African Transport Conference (SATC 2007)

[71] Steyn W. JvdM (2011) Applications of Nanotechnology in Road Pavement Engineering, Nanotechnology in Civil Infrastructure

[72] Stryk and Pospil, (2009) Non-destructive testing of pavement conditions (presentation CERTAIN workshop Tallinn)

[73] Symonds Group Ltd., in association with ARGUS, COWI and PRC Bouwcentrum (1999) Report to DGXI, European Commission Construction and Demolition Waste Management Practices, and their Economic Impacts

[74] Tadesse, D. (2010) The impact of climate change in Africa. Pretoria: Institute of Security Studies.

[75] The Australian Environmental Protection Agency (EPA) (2009), Waste Guidelines: Waste definitions, EPA 842/09

[76] The blue book - Australian Waste Industry (2008): 2007/08 Industry and Market Report, North Sydney, N.S.W. : WCS Market Intelligence

[77] The Government of the Republic of South Africa (2011) National Climate Change Response – The White Paper, Department of Environmental Affairs.

[78] The Institution Recycling Network (2005) Recycling Construction and Demolition Wastes: a guide for architects and contractors, http://www.ir-network.com/documents/CDRecyclingGuide.pdf

[79] The U.S. Environmental Protection Agency (2009) Reduce, Reuse, and Recycle Construction and Demolition Materials at Land Revitalization Projects

[80] The US Environmental Protection Agency (EPA) (2009), Construction and Demolition (C&D) Debris http://www.epa.gov/reg3wcmd/solidwastecd.html

[81] Theyse H L, M de Beer, Rust F C, (1996) Overview of the South African Mechanistic Pavement Design Analysis Method

[82] United Nations Framework Convention on Climate Change (UNFCCC) (2011), Kyoto Protocol, UNFCCC, retrieved 9 December 2011

[83] Vegas I., Ibañez, J.A., San José, J.T. and Urzelai, A. (2008) Construction demolition wastes, Waelz slag and MSWI bottom ash: a comparative technical analysis as material for road construction. Waste Management 28(3)

[84] Wang, J. Y., Touran, A., Christoforou, C. and Fadlalla, H. (2004) A system analysis tool for construction and demolition waste management. Waste Management 24 (10)

[85] Washington State County Road Standards. *Chapter 35.78 RCW requires cities and counties to adopt uniform definitions and design standards for municipal streets and roads*. Municipal Research & Services Center of Washington. (2005) Retrieved 2007-04-20.

[86] Wathne L and Smith T (2007) Green Highways North America concrete paving Industry’s Perspective. Theme IC. In CD Proceedings: 10th International Symposium on Concrete Roads, 18-22 September 2006, BRUSSELS, BELGIUM

[87] Wood E. (2011), Greening South Africa Industry, Sustain

[88] Yeung, A.T., Mok, K.Y., Tham, L.G., Lee, P.K.K., and Pei, G. (2006). "Use of inert C&D materials for seawall foundation: A field-scale pilot test." Resources, Conservation and Recycling, 47(4), 375-393.

[89] Yuan D., Nazarian S., Chen D., McDaniel M. (1999) Use of Seismic Methods in Monitoring Pavement Deterioration During Accelerated Pavement Testing with TxMLS, A Paper for Presentation and Publication of The 1999 International Conference on Accelerated Pavement Testing, Reno (Nevada)

[90] Zammataro S. (2010) Monitoring and assessing greenhouse gas emissions from road construction activities: the IRF GHG calculator, for the International Road Federation World Meeting, 16th, 2010, Lisbon, Portugal

Chapter 3

3 Management of Construction and Demolition Waste and its use for road construction in a South African Municipality

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Abstract

The management of Construction and Demolition (C&D) waste material plays a relevant social, economic and ecological role in contemporary world. Due to lack of space in the disposal sites, reuse of potentially recyclable material is vital. Finding alternative usage for waste materials is a challenge for municipalities that want to decrease the volume in landfill sites and also a challenge for scientists who want to reduce the environmental impact of these waste materials by promoting alternative uses. An effort in this direction will help and encourage a new economy in equilibrium with the growing necessity of environmental preservation. Moreover, the natural aggregates that are needed for construction purposes have reached inadequate levels today and the establishment of new quarries is discouraged by administrations.

This paper is specifically focused on the C&D waste stream produced in Durban Metropolitan Area, South Africa, with suggestions for its management and recycling. Origin and quality of this material disposed at the Bisasar Road landfill site were investigated and tested to determine its suitability for road pavement uses. The replacement of natural soils with

unconventional waste materials is strongly recommended to minimize the use of open quarries for natural aggregates.

The alternative material studied in this research attains the same mechanical performance as natural aggregates despite having different physical characteristics, demonstrating that C&D waste can replace natural aggregates when specific management procedures are performed to mitigate the intrinsic heterogeneity observed in the material. The results obtained from this study demonstrated good performance of the C&D material as base, sub-base, or subgrade material depending on the road category.

Keywords: Construction and demolition waste, waste management, waste stream, recycling, laboratory road tests

3.1 1 Introduction

Wastes nowadays are no longer considered as unwanted material but have become important resources in several fields as sustainable replacement of raw materials. Construction and demolition (C&D) materials are a particular type of solid waste. They are universally defined as debris derived from construction, renovation or demolition of buildings as well as roads, bridges and dams. Various components such as concrete, metals, wood, asphalt and roofing are included in this material (Franklin Associates, 1998).

C&D is classified by the European Waste Catalogue (EWC) into nine categories (Environment Protection Agency, EPA, 2002) as shown in Table 3-1.

Table 3-1 chapter 17 of European Waste Catalogue: C&D classification (EPA, 2002)

Chapter_17 Construction and demolition wastes (including excavated soil from contaminated sites)
17_01 concrete, bricks, tiles and ceramics
17_02 wood, glass and plastic
17_03 bituminous mixtures, coal tar and tarred products
17_04 metals (including their alloys)
17_05 soil (including excavated soil from contaminated sites), stones and dredging spoil
17_06 insulation materials and asbestos-containing construction materials
17_08 gypsum-based construction material
17_09 other construction and demolition waste

In 1975, to encourage proper waste management, the first waste framework directive was released by the European Union (EU). This directive led to the concept of waste hierarchy, as explained in the directive 2008/98/EC, which classifies the possible operations of waste management from the most advantage option to the less one as shown in Figure 3-1.

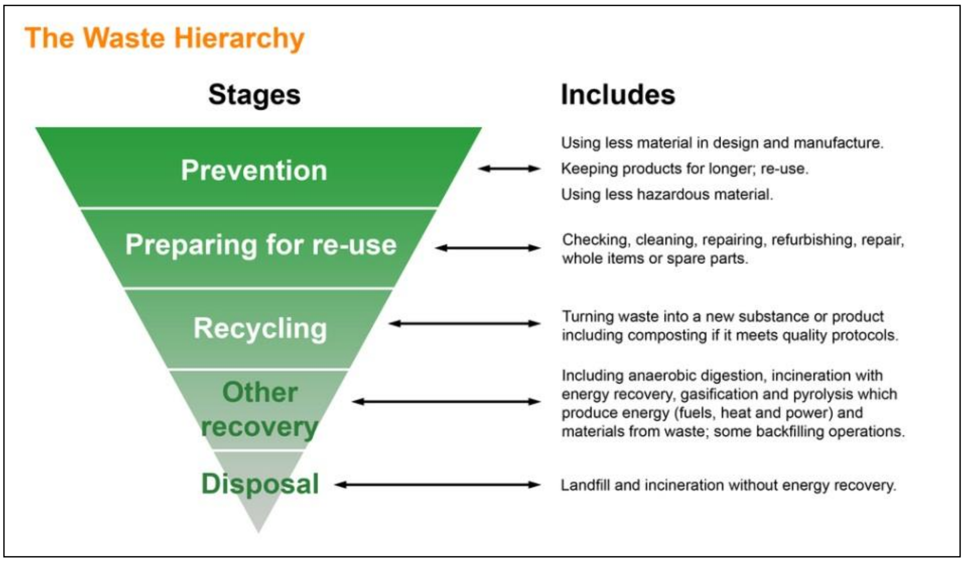

Figure 3-1 The Waste Hierarchy (Marlow, 2012)

Every year civil construction works consume large amounts of natural resources and consequently produce a proportionally high volume of construction waste. The USA registered 136 million of tons from of building-related C&D debris alone (Franklin Associates, 1998), while in Europe, 450 million tons are produced every year (EEA, 2002). The city of Hong Kong generated 20 million tons in 2004 (Poon et al, 2007).

For this reason, proper management strategies for treatment and stockpiling of this material must be implemented depending on the quantity and quality of the C&D waste material produced. These actions can be anticipated by carrying out a detailed analysis before the building permits are issued in the area (Wang et al., 2004). The final composition of C&D material depends on shape and size of the building, main construction materials used, period and techniques of construction and demolition of different civil works (Kourmpanis et al. 2008). C&D waste is, therefore, considered as heterogeneous material (Paschoalin et al, 2012).

C&D waste materials are also generally inert (Franklin Associates 1998), which could entail simple recovery with potential economic advantages for the industry. Alternative resources can partially or completely replace natural aggregates (Bairagi et al., 1993) having the potential for preserving natural resources.

The production of construction materials, derived from natural resources, requires a conspicuous use of energy which can be intensely reduced by reusing the C&D waste (Dolan et al, 1999) with a reduction of carbon emissions generated (Carmody et al, 2011). Worldwide the construction industry has been estimated to be the cause of 12-16% of the fresh water consumption, 25% of wood harvested, 30-40% of energy consumption, 40% of virgin materials extracted, 20-30% of greenhouse emissions (Macozoma, 2006). The reuse of waste also reduces the amount of material stockpiled in landfill-site, increasing the life and preventing the dereliction of pristine areas (Inyang 2003).

Moreover, the scarcity of suitable aggregates for roads construction has increased the cost of natural aggregates. In this context, the road design (Coni et al, 2012) and road rehabilitation (Paige-Green and Ware, 2006) have been considered with alternative materials. However, there are no proper specifications for alternative materials for road design yet; consequently standard road tests for natural aggregates have been used on C&D waste (Leite et al, 2011).

The C&D waste is commonly utilized as a construction material in developed countries but, in South Africa, it has not found yet a prevalent use. The application of this material in road construction is scarce, mainly due to the lack of understanding of the quantity and the quality of debris produced and because of the complexity of the specifications in the country. The aim of this research is to show the applicability of the C&D material coming from Bisasar Road landfill site, as a component of sub-base and subgrade, in the South African perspective.

In the end preliminary tests were conducted in the UKZN laboratory in order to assess the properties of C&D waste material collected from Bisasar Road site and to give suggestions for its application in road construction.

3.2 Management of C&D waste in South Africa

South Africa plays the leading role for driving the economy of the entire African continent through the development of new technologies for environmental protection. The continent does not contribute excessively to greenhouse gas emissions but it does not have the ability to cope with the impacts of climate changes and as a result would suffer the worst consequences (Tadesse, 2010). For this reason South Africa has drafted a White Paper on the National Climate Change Response to meet its responsibility and contribute to the international effort to mitigate the climate change. The paper outlines policies, principles and strategies that the country will use to respond to climate change. The country is also signatory of the United Nation Framework Convention on Climate Change (UNFCCC) and for encouraging a sustainable growth South Africa hosted the 17th Conference of the Parties (COP17) in December 2011, in Durban.

The management of C&D waste helps to combat the climate change, but in South Africa this material has found only few uses so far (Macozoma, 2006). The material is recycled and used in low level applications such as backfilling, landscaping, site levelling and other landfill purposes, and very rarely in high level application such as road construction, buildings, housing or others. A detailed study and analysis of C&D waste production has not been conducted so far in the country. It is estimated that the construction industry alone generates 5-8 million of tons every year but just 1 million tons are reported in the national landfill sites records (Macozoma, 2006).The poor collection of this material can be explained by the non-uniform classification in the landfills and the deficiency of a weight-bridge at some of these sites (Macozoma, 2006). This waste is generally stockpiled in specific areas in a landfill site or stored in containers on site or in containers for reuse or recycling. However, the presences of illegal dumps are considerable (Macozoma, 2006).

The Durban Metropolitan Area (DMA), administered by eThekwini Municipality, is an example of a large African city where both formal and informal areas are present. It has a population of 3.5 million inhabitants (Community Survey, 2007) and covers a surfacearea of 2295 km^2 with population density of 1513 per km^2 (Municipal Demarcation Board, 2008).

In 2004 The Municipal Climate Protection Programme (MCPP) has been issued to effort the greenhouse gases reduction working with a pro-poor plan. It, in particular, assesses the local impacts, develops tools to assist strategic decision making in the city of climate change in the area, highlights the key interventions and concerns mainstreaming into city planning and development (eThekwini Municipality, 2010).

Figure 1 shows the Waste Hierarchy which helps control and prevention of gasses emission and presently in Durban, and also in South Africa, the reclaim is very low. The waste produced in the DMA is stored in three main sites: the Bisasar Road landfill located close to the city centre, the Marianhill landfill in the western area and the La Mercy landfill in the north of the area (Couth et al, 2011).

3.3 Rationale of the research

The Bisasar Road landfill was selected as case study for this research since it is recipient of the largest part of the waste coming from the DMA. It is operated by Durban Solid Waste (DSW) and, with its area as 44 ha, is the biggest landfill site in Durban and one of the biggest in South Africa. This landfill site was established in 1980 and was expected to be closed in 2013 (Couth et al, 2011). It is situated 7 km from the Central Business District (CBD) and closes by the main residential suburbs such as Berea, Westville, Umhlanga, and important industrial areas such as the harbour, Pinetown and Springfield.

The waste collected at this site is classified in 9 categories. In Table 3-2 a brief description of these types of waste is presented.

Table 3-2 Bisasar road landfill site classification (eThekwini, 2003)

Code	Product type	Description
01	DSW (Durban Solid Waste)	general waste comes from eThekwini's trucks
02	General Solid Waste	general waste from private vehicles
03	Garden Refuse	waste from gardens or parks, as leaves, grass, roots and brands
04	Builders Rubble	aggregates which are bigger than 400mm
05	Mixed Loads	aggregate or other material, which are not consistent and thoroughly mixed together
06	Sand and Cover Material	sand and small aggregates generally arrive from

		construction sites
07	Purchase and cover material	material used to cover the solid waste
08	Tyres	old tyres from any vehicles
09	Light Type Refuse	paper, plastic and can
10	Other	general waste from shopping malls

The incoming waste is labelled according to this classification; it is, then weighed and addressed to a specific area in the site. The incoming waste tags as "builders rubble" and "sand and covers materials" are part of C&D category as per the classification given by the EWC as shown in Table1.

The waste stream to the landfill was investigated through the analysis of the past data provided by the management company. The study demonstrates that among all kinds of waste material getting deposited at the site, the C&D waste represents a significant portion of the main flow.

This new research focuses on a more accurate characterization of the incoming C&D waste material and its geographical origin by means of the results of a survey supplied at the entrance of the landfill. The analysis of the data collected allows visualization and more specific consideration of the waste streams. Moreover a new classification of C&D waste was introduced in order to anticipate the quality of this material and to encourage preliminary sorting on site.

The C&D material disposed in Bisasar Road, which was analysed by means of laboratory tests, demonstrated its suitability for use in various civil works especially in road construction due to the large request of aggregates.

3.4 Results and discussion

3.4.1 Waste stream

To understand the total quantity of waste material coming at the landfill site at different durations of time and for identification of the main constituents received during the period, data is collected from the land fill site. The landfill site data is analysed to understand the material.

3.4.1.1 Data provided by DSW

Two groups of data for years 1995-1998 and 2009-2012, provided by The Cleansing and Solid Waste Unit of eThekwini Municipality were analysed. Figure 3-2 highlights how the average incoming waste stream increases by 50% over a period of almost 13 years. The recent growth of the country can explain such an increase in the solid waste produced with time, partially coinciding with the preparative work for the Soccer World Cup in 2010.

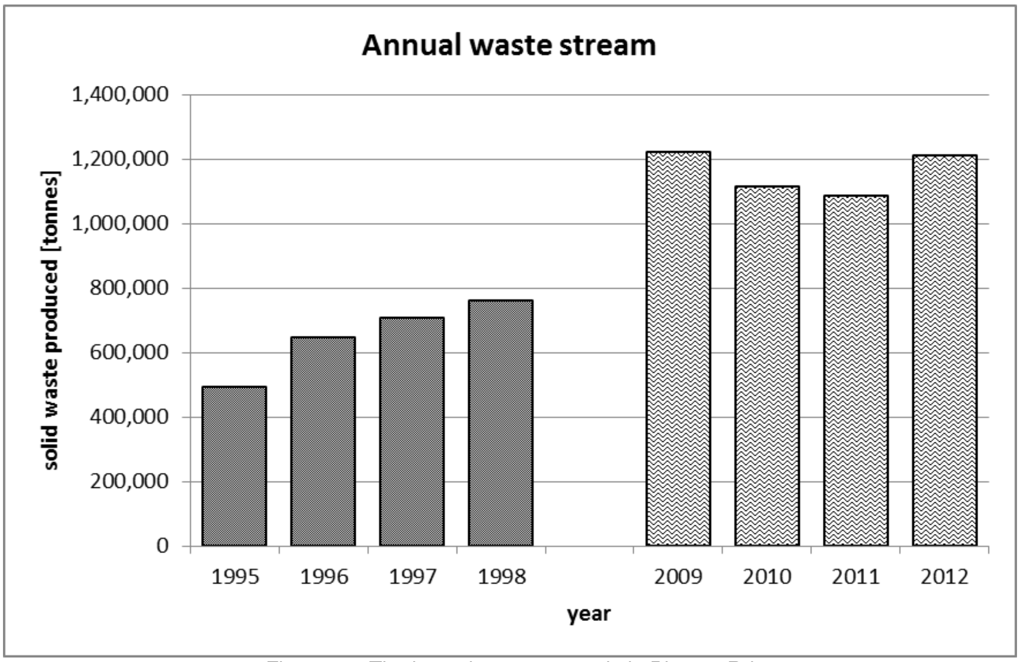

Figure 3-2 The incoming waste yearly in Bisasar Rd

Figure 3 shows the distribution of flows by type of waste as analysed by using the waste data provided by DSW from 2009 to 2012. The figure shows the average annual percentage distribution by weight of various constituents. The flows are gathered in an excel sheet and divided by product types as described in Table 3-2.

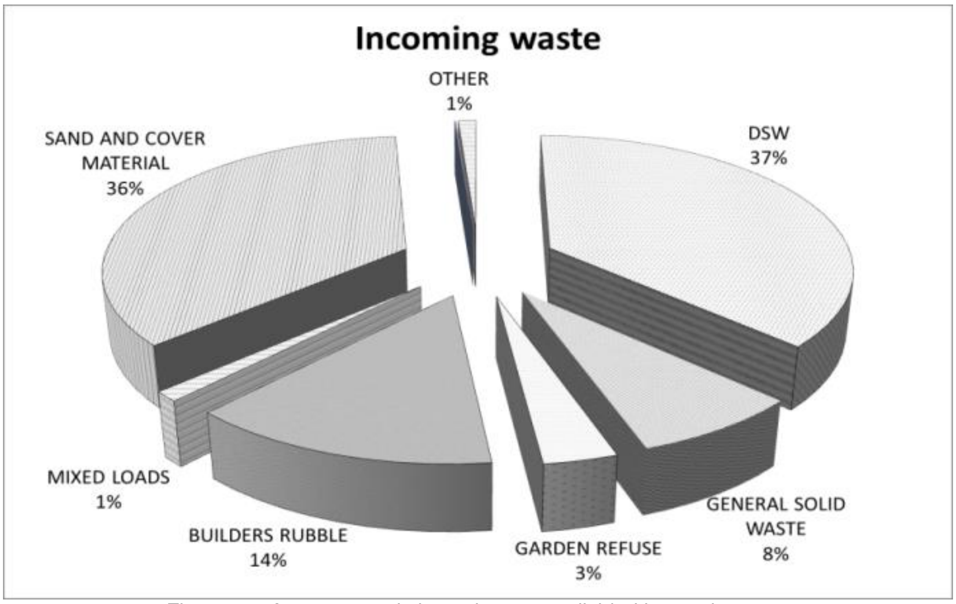

Figure 3-3 Average yearly incoming waste divided by product type

The two major waste streams entering to the Bisasar Road landfill site are general waste (product type code 01, 02 and 10) and the C&D waste (product type code 4 and 6). As can be observed from Figure 3-3, C&D waste which mainly consists of the “sand and cover materials” plus “builders rubbles” reaches almost 50% of the total waste amount. That means that the half of the stream coming to the landfill can be reused or recycled, eliminating materials from disposal and giving new spaces in the landfill. Afterwards an example about how to reused rubble and sand and cover materials is reported.

In Figure 3-4, the generation of C&D waste collected every year at the Bisasar Road Landfill site for a period of eight years is plotted. It can be observed from this data that the C&D waste material had suddenly increased considerably during 2009 probably due to the construction and modernization of sports facilities and hospitality that the DMA needed for the event in 2010. Though the trend shows slowdown in 2010 and 2011 but increased in 2012 and is likely to increase in future due to large scale construction activities for major infrastructure development. A trend line was plotted which shows a future production of C&D waste may increase reaching 800,000 in 2020.

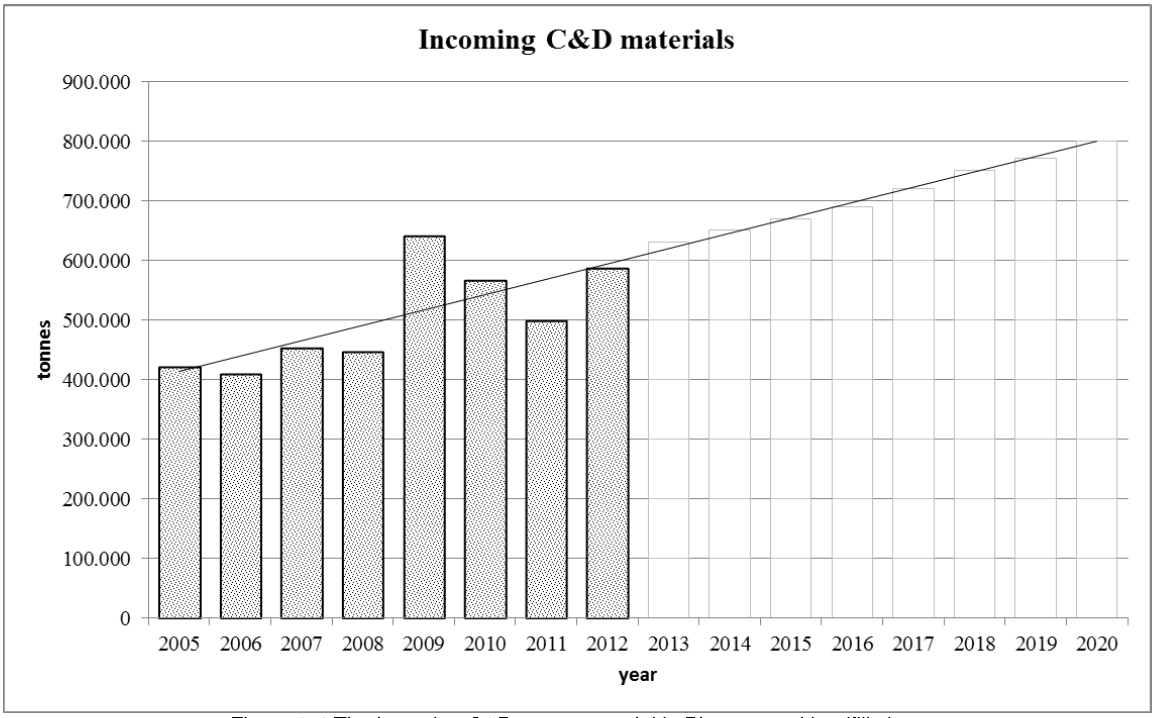

Figure 3-4 The incoming C&D waste material in Bisasar road landfill site

3.4.1.2 Production of C&D waste in DMA

To understand the areas from which major portion of the C&D waste was being generated and brought to the Bisasar Rd landfill site, a survey was conducted by interviewing drivers at the weight bridge facilities at the entrance of the landfill. The questionnaire is attached in

Appendix A at the end of this manuscript. Based on this interview a questionnaire was filled giving detail of the truck drivers bringing C&D waste to the site. To identify the details of C&D waste arrived in, specifically the study concentrated on its amount and its composition. The incoming C&D waste stream was analysed based on the data collected from about 1000 questionnaires filled in a period of three months, from June to July 2010.

Each questionnaire is divided in three sections. The first part is about the general information of the vehicle and its type. The second part deals with weight bridge data, the category of C&D material transported and its mass. The last part focuses on the area of origin, the type of site from where the C&D waste originated and likelihood of receiving larger volumes from the same site.

Only about 9% of the C&D waste is disposed to landfills by private vehicles, while the remaining 91% by construction or demolition companies. This waste material, stored in specific areas of the site, consists of 64% “sand and cover material” and 36 % “builder’s rubble”. However, the classification provided by DSW is not sufficient for a precise identification of the various components of the debris. The results of the investigations suggest implementing a new classification based on the source of the C&D waste, which, in turn, influences its characteristics. The most common sources of C&D in the Durban Municipal Area are highlighted in Figure 3-5. It tries to recognise the nature of C&D materials and could predict the mechanical and physical properties, hence it is possible to separate them for type. Sand and aggregates are present in all categories especially in excavation works and roads construction and rehabilitation. Excavation works and rehabilitation of roads generally are composed of natural materials as sand, soils, aggregates, etc. Moreover since 42% of the C&D material is originated from building works, which means demolition of blocks and houses, it is possible to assume a high quantity of concrete and brickworks contained in it.

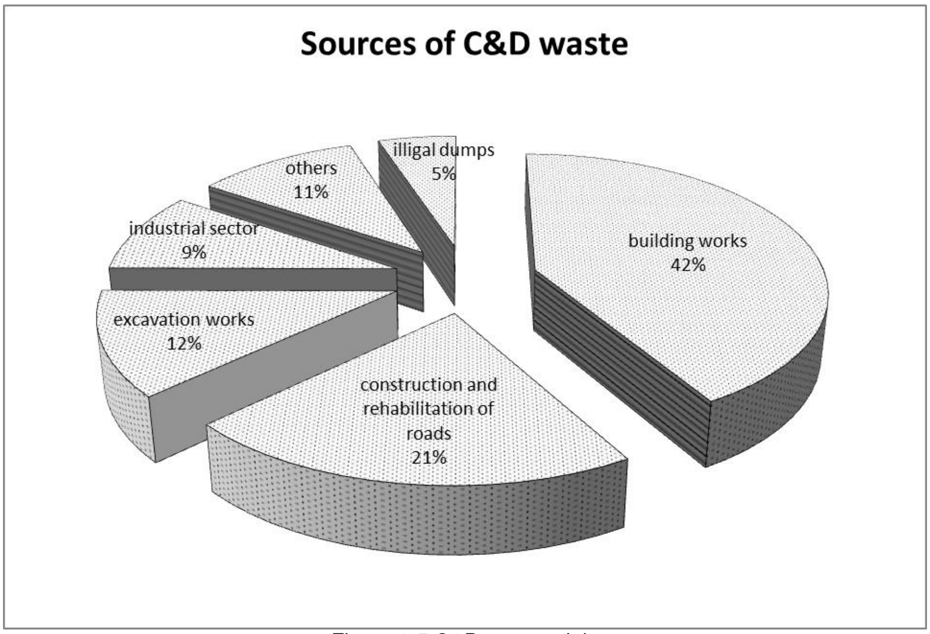

Figure 3-5 C&D waste origin

It would be advantageous to prevent mixing these materials coming from different sectors, and it would be better to keep them in separate stockpiles which will have relatively homogenous characteristics, to avoid sorting on site, in view of the recycling process to be adopted for each of these materials.

The Figure 3-6 shows the areas covered under the Durban Metropolitan Area (DMA) and the relative C&D waste stream percentages generated and brought to the landfill site. The concentric circles indicate the distance of the areas from Bisasar Road landfill. It may be observed that 98% of the total waste stream comes from within 25 km radius of the landfill site.

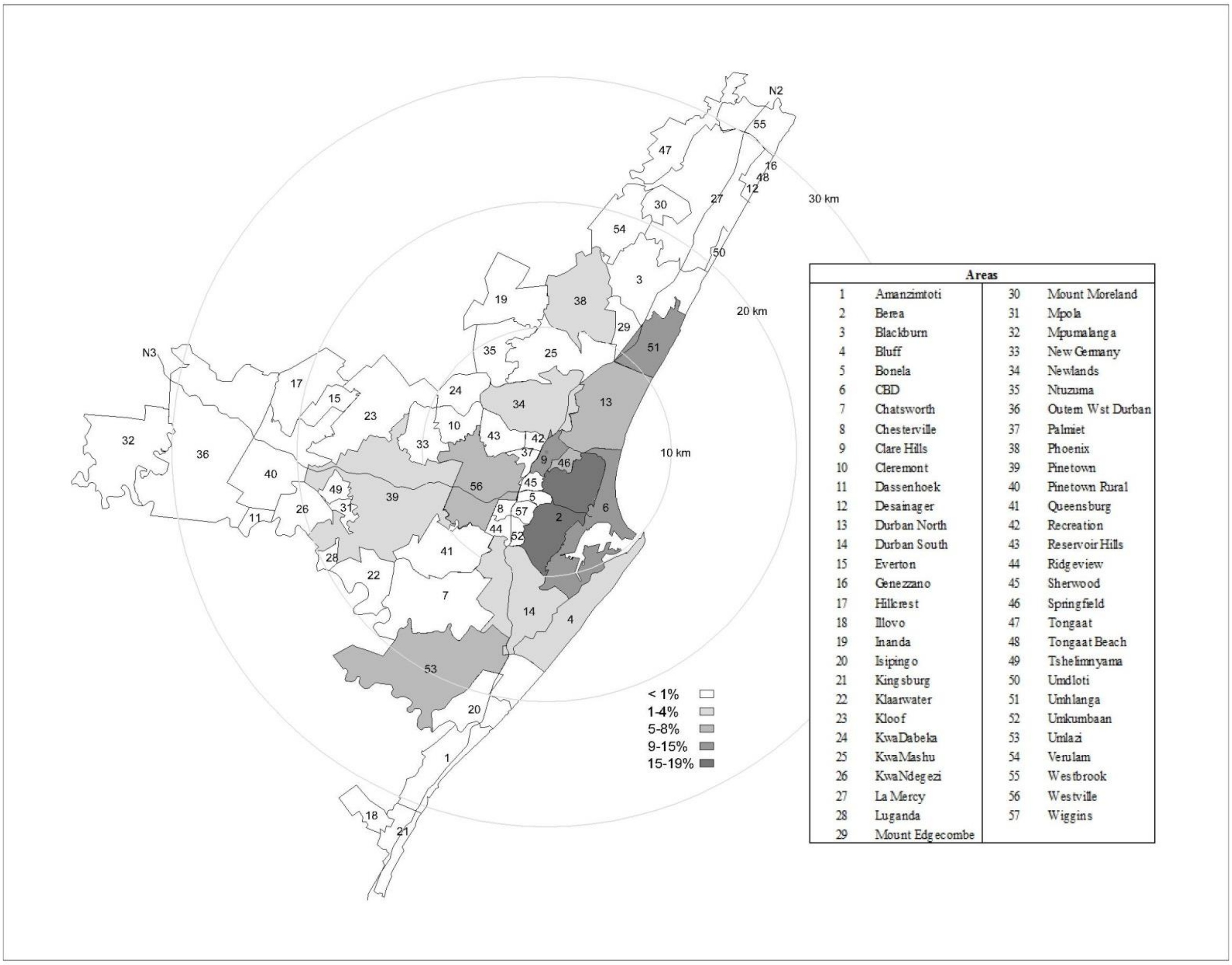

Figure 3-6 The map of distribution of flows in DMA

The quantity of waste produced in each area is directly influenced by the development or construction activity taking place in that area. Table 3-3 shows the distribution of the C&D waste area for the areas which are contributing more than 1% of the total flow. The major C&D waste producers are the densely populated residential suburbs such as Berea and Central Business District (CBD) and the developing areas such as Umhlanga and Umlazi. Industrial districts do not generate a large flow unless affected by extensive civil works as in the case of Clare Hills where the new Umgeni interchange, is under construction. The first five areas listed in the table produce more than 65% of the total C&D waste stream to the landfill site. The table presents the classification of landfill material as suggested by DSW and also the one obtained on the basis of the survey conducted in this study.

Table 3-3 The distribution of flows in the DMA

Area	**TOT**	**landfill classification**		**survey classification**					
		builders rubble	sand and cover material	building works	construction of roads	industrial sector	illegal dumps	excavation works	others
Berea	19.07%	8.56%	10.51%	13.62%	1.17%	1.17%	0.00%	1.56%	1.56%
Clare Hills	15.18%	0.39%	14.79%	0.00%	8.95%	0.00%	0.00%	5.45%	0.78%
CBD	13.62%	6.23%	7.39%	4.67%	3.50%	1.56%	0.00%	0.78%	2.33%
Umhlanga	9.73%	4.28%	5.45%	7.00%	0.39%	0.39%	0.00%	0.39%	1.56%
Umlazi	7.78%	0.00%	7.78%	0.78%	0.78%	0.78%	3.89%	0.00%	1.56%
Durban North	5.45%	3.89%	1.56%	3.11%	0.00%	1.17%	0.00%	0.39%	0.78%
Westville	5.45%	2.33%	3.11%	2.33%	1.17%	0.39%	0.00%	1.56%	0.00%
Springfield	5.06%	1.56%	3.50%	1.95%	1.56%	1.56%	0.00%	0.00%	0.00%
Bluff	3.11%	0.78%	2.33%	0.78%	0.00%	0.39%	0.78%	0.39%	0.78%
Durban South	2.33%	0.39%	1.95%	1.17%	0.00%	0.00%	0.00%	0.00%	1.17%
Phoenix	1.95%	1.17%	0.78%	0.78%	0.78%	0.39%	0.00%	0.00%	0.00%
Pinetown	1.56%	0.78%	0.78%	1.17%	0.00%	0.39%	0.00%	0.00%	0.00%
Newlands	1.17%	0.00%	1.17%	0.39%	0.78%	0.00%	0.00%	0.00%	0.00%

The establishment of new temporary storage areas or using the existing landfill sites\dumps will reduce costs due to transport and landfilling and would encourage the use of C&D waste as a substitute of natural materials. The shortest transport distance may help to reduce the traffic congestion and carbon emission in a crowded territory.

3.4.2 **Preparation of the aggregates for road construction**

The C&D waste is heterogeneous regarding its composition and particle size distributions. The grading distribution must be therefore modified as required in the specifications relative to planned purpose (Huang et al, 2002). The heterogeneity of the C&D is a characteristic element that cannot be eliminated (Paschoalin et al, 2012) but that can be limited through a proper management of this resource. However, it is important to statistically verify that the characteristics of the aggregate fall within the limits required by the specifications. In South Africa, characteristics and properties of the aggregates for road construction are listed in the Technical Recommendation for Highways (TRH) and in the Committee of Land Transport Officials (COLTO) standards specifications for road and bridge works.

In this research a representative amount of C&D waste of Bisasar Road landfill site was prepared to obtain road aggregates in accordance to the national specifications. In Figure 3-7, the four machines used during the preparation of the waste material to obtain suitable grading curve (one loader, one excavator, one screener Atlas Copco HCS 3715 and one impact crusher Atlas Copco PC1060) are shown.

Figure 3-7 Screener and crusher working in Bisasar Rd landfill site

The proposed screening and the crushing procedure followed the scheme of Figure 3-8. The maximum aggregate size was chosen to allow the use of the material in road base and sub-base.

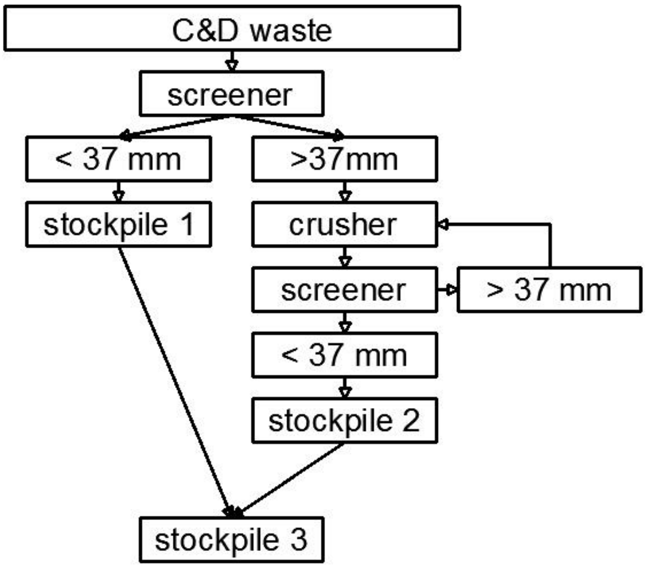

Figure 3-8 Screening and crushing scheme

Stockpile 1, result of a preliminary sieving using 37 mm size sieve, is observed to mainly contain fine material with high percentages of sand. The remaining material having particle size more than 37 mm, was crushed to obtain the necessary maximum size and was stored in stockpile 2. From these stockpiles samples were collected for specific laboratory tests. With material coming from the two stockpiles a blend (Stockpile 3) was created by mixing of 50% of stockpile 1 and 50% of stockpile 2 materials. Samples of this blend were also tested.

3.4.3 Laboratory test

Tests on the three samples were conducted in accordance to the national standards (TMH1). The tests should assess the suitability to reuse C&D waste as road aggregates in regard to the desired properties in the TRH and COLTO standards.

In South Africa the road pavement design shows different procedures than those suggested in other countries. Three types of pavement design are present in the South African Pavement Catalogue which are divided in relation to the base layer (granular, hot-mix asphalt or cemented). The design with granular base needs particular attention because it has to withstand high loads for this type of material. It is characterized by a thin layer in HMA which is supported by an unbound layer as base, a cemented layer as sub-base and unbound granular layers as foundation (TRH4, 1996).

COLTO classification requires a series of standards for the aggregates. It uses grading curves, Atterberg limits, shape of the aggregate, strength, swell, durability and soluble salt for making complete geotechnical analyses of the material. By means of that, the aggregates are classified from G1, the best material to the G10, the worst.

For comparison purposes, the material was also classified by the international classifications: the AASHTO classification reviewed by the Highway Research Board (HRB) in 1945 and Unified Soil Classification System (USCS) suggested by Casagrande in 1942.

Before the beginning of the laboratory tests, “unwanted” impurities such as wood, grass, cardboard, metals, rubber and plastic were found and manually removed from the samples. The crusher used at Bisasar Road site can retain metal components by means of internal magnets, therefore metallic waste was only noticed in samples from stockpile 1 and stockpile 3. In all cases, the impurity did not exceed 1% by mass in each sample.

Sieve analysis

The grading curves of sample 1, sample 2 and sample 3 are shown in Figure 3-9 and tests were performed according to TMH1-methodA1. In Table 3-4, the results of sieve analysis are presented along with the requirements of G4 and G5 material to be used as a reference which indicates a grading for good base and sub-base layers.

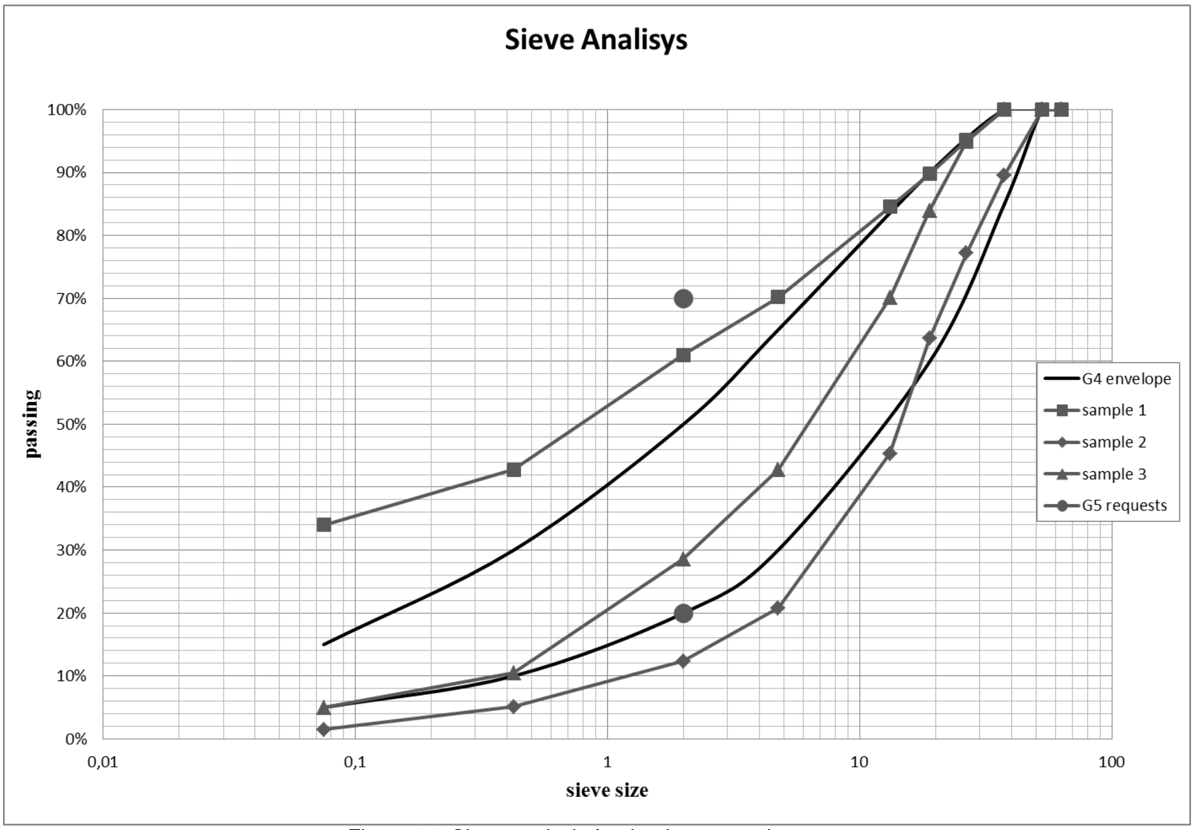

Figure 3-9 Sieve analysis for the three samples

Table 3-4 shows that the sample 1, gives the highest percentage of fine and not fall within the G4 grading envelope. Sample 2 falls into G4 envelope and the Sample 3 contained more coarse aggregates.

Table 3-4 Sieve Analysis results

sieve size	**Passing**						
	sample 1	**sample 2**	**sample 3**	**G4 envelope**		**G5 requirement**	
[mm]				min	max	min	max
53	100.00%	100.00%	100.00%	100%	100%		
37.5	100.00%	89.55%	100.00%	85%	100%		
26.5	95.14%	77.16%	94.92%	-	-		
19	89.75%	63.64%	83.91%	60%	90%		
13.2	84.51%	45.31%	70.05%	-	-		
4.75	70.20%	20.77%	42.77%	30%	65%		
2	61.01%	12.34%	28.60%	20%	50%	20%	70%
0.425	42.78%	5.14%	10.50%	10%	30%		
0.075	34.00%	1.49%	5.00%	5%	15%		

Atterberg limits

The specification for Atterberg limits followed the TMH1-method A2 for the liquid limit and the TMH1-methodA3 for plastic limit and plasticity index. The Liquid Limit and Plastic Limit of the material could not be determined, due to the negligible presence of clay minerals; therefore the material was described to be Non-Plastic (NP). Indeed concrete, brickworks and sand are the main materials which compose C&D and they do not have clay and indicate a good behaviour in relation of water content (Vegas et al, 2008).

Compaction test

In the TMH1 the procedure that describes the compaction test is the method A7. C&D waste materials have lower density than virgin aggregates and require greater water quantities for compaction, probably due to the porosity of the material. The optimum moisture content (OMC) was higher than typical soils and ranged between 8.2% to 12.5% compares to 5-6% (Barbudo et al., 2011). Sample 1 attained a maximum dry density (MDD) of 19.15 kN/m^3, higher than other samples because of the nature of the fine material allows having less void space. Sample 2 and sample 3 attained the maximum densities of 17.87 and 17.63 kN/m^3 respectively as shown in Table 3-5.

Table 3-5 Compaction test results

compaction test	**OMC**	**MDD**
sample	[%]	[kN/m^3]
1	8.20%	19.15
2	9.80%	17.63
3	12.50%	17.87

It is interesting to note that the incoming C&D waste material received each day (an average of 3,288 t) at the landfill site, with the maximum dry densities as obtained in this study was found sufficient for the construction of a typical freeway road 1 km long, 7.2 m (two lanes) wide and 150 mm thick.

California Bearing Ratio (CBR)

The TMH1-method A8 was used for the soaked CBR test. The Sample 3, which is coarser material, was able to withstand a higher vertical penetration resulting in a much higher CBR than the Sample 1, which is a fine material. Table 3-6 gives the results of the CBR values at 93%, 95%, 98% and 100% of compaction described previously. South African specification checks the CBR value at 98%, 95% or 93% in order to classify the material in the right category. The swell was assessed with a value of 0.2% for each sample and confirmed the non-plasticity of the material.

Table 3-6 CBR test results

sample			@93%	@95%	@98%	@100%
1	dry density	[kN/m^3]	17.80	18.19	18.76	19.15
	CBR	[%]	7.00	25	36.00	38.00
2	dry density	[kN/m^3]	16.39	16.74	17.27	17.63
	CBR	[%]	48	51	62	68.6
3	dry density	[kN/m^3]	16.66	17.02	17.56	17.92
	CBR	[%]	30.00	35	39.00	52.91

3.4.3.1 Classifications

In order to classify the material three classifications have been used. The USCS describes the texture and grain size of a soil and all samples were defined as SW, "well-graded sand, fine to coarse sand". The HRB and COLTO are the classification used to identify the C&D material characteristics for road construction purposes. The HRB classification considers both the grading and the Atterberg limits, sample1 was classified as A2, its fine content were much higher than A1 limit. Sample2 and sample3 were classified as A1a, which denotes an excellent material for any layer.

The use of a suitable classification for C&D material would be more appropriate but the lack is both nationally and internationally

Table 3-7 summary table

sample	PI	OMC	MDD	CBR@95%	CBR@93%
1	NP	8.2%	19.15 kN/m^3	25%	7%
2	NP	9.8%	17.63 kN/m^3	51%	48%
3	NP	12.5%	17.87 kN/m^3	35%	30%

The South African classification is more elaborate and Table 3-7 summarizes the required parameters of each sample to identify the material type. It considers several parameters ranging from the evaluation of the grading to the bearing evaluation of the compacted material. Through these preliminary tests Sample1 could be considered as G10, material for subgrade; Sample2 should be in G6 group because it showed a low CBR, as well as Sample3, the CBR is higher than 45% at 95% of compaction but its grading does not meet the specifications that require passing 2 mm higher than 20%.

3.4.4 **Current usage of C&D at the Bisasar road landfill site and suggestion for a future application**

As per the information collected at the landfill site, currently the applicability of C&D waste in road construction is demonstrated by constructing an internal road system at the landfill site entirely built with rubble that allows the daily transit of heavy trucks. The DSW encourages the collection of this material with particle sizes smaller than 200 mm without contaminants. For construction of haul roads with this material, one meter of C&D waste material is laid down on the waste body using a dozer, then wetted with a water tanker and compacted using a 10 ton padfoot roller. Aggregates bigger than 200 mm are landfilled to create stable areas such as pioneering platforms for handling. On site earthmoving plant consists of dozers, compactors, graders and water tankers. The haul roads constructed using C&D waste material is performing satisfactorily though they do not look at ridibilty and mobility. No other technical details or research are available from the landfill. They have just collected the rubble in the area and almost roughly spread for their internal road.

The results of the study performed and the large quantity of inert material stored in the metropolitan area hint the idea of an extensively reusing the C&D material in the road construction business. Different layers of a natural aggregate road base and sub-base can be replaced by a C&D waste because of equivalent geotechnical properties and the massive availability in the landfill sites.

3.5 Conclusions

A preliminary investigation about quantities and properties of the C&D waste material generated in the Durban Metropolitan Area has been carried out demonstrating advantages related with its reuse. The amount of this reclaimed material is, indeed, enough for the effective use in road construction.

The waste management performed at Bisasar Road landfill site may be just implemented at other sites without a drastic alteration of the collection and storage system already in use. However a detailed study of the road metropolitan network, landfill sites, position and dimension of construction sites can help to develop a system for C&D waste disposal at intermediate stockpiling areas to encourage the reuse of C&D material wherever applicable. It would be advantageous, when possible, stocking the C&D waste in different places within the landfill site according to its nature and its grading in order to simplify the reuse. Moreover, avoiding the collection of C&D waste at only a small number of landfill areas, the economic and environmental cost of its transport can be reduced.

This study demonstrates that the recycling of C&D material can replace an equivalent G6, potentially G5, natural aggregate which is suitable for sub-base and subgrade layers in road construction according to South African pavement design criterion. In the HRB classification it was classified as A1a, which is the best option.

Further studies should be performed for a better understanding of its properties and behaviour through more laboratory tests and instrumented full-scale models.

Acknowledgements

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References

[1] AASHTO M 145-91 (2008) Standard specification of soils and soil-aggregate mixtures for Highway *Construction Purposes*. American Association of State *Highway* and Transportation Official.

[2] AASHTO (1982) Standard Specifications for Transportation Materials and Methods of Sampling and Testing, Part I and Part II. Washington D.C. American Association of State Highway and Transportation Officials

[3] Bairagi, N.K., Ravande, K. and Pareek, V.K. (1993) Behaviour of concrete with different proportions of natural and recycled aggregates. Resource Conservation and Recycling 9: 109–126

[4] Barbudo, A., Agrela, F., Ayuso, J., Jiménez J.R. and Poon C.S. (2012) Statistical analysis of recycled aggregates derived from different sources for sub-base applications. Construction and Building Materials 28 (1): 129-138

[5] Bio Intelligente Service (2011) Serviced contract on management of construction and demolition waste – SR1 Final report

[6] Carmody, J., Strong, R. and Jacobson, R. (2011) The Minnesota Site and Building Carbon Calculator. (Prepared by the Center for Sustainable Building Research --

2/24/2011 Page 28 - Regents of the University of Minnesota, Twin Cities Campus, College of Design) http://www.csbr.umn.edu/download/CarbonCalculator-Final.pdf

[7] Casagrande A. (1948) Classification and Identification of Soils. Transactions of American Society of Civil Engineering 113: 901–930

[8] Committee of Land Transport Officials (COLTO) (1998) Standard specification for road and bridge works. Pretoria: the South African Institution for Civil Engineering (SAICE)

[9] Committee of State Road Authorities (1985) Technical Recommendations for Highways – Guidelines for road construction materials TRH14. Pretoria: Department of Transport.

[10] Coni, M., Rombi, J., Zedda, V., Portas, S. and Pistis S. (2012) Monitoring the Performances in Real Working Conditions of C&D Waste Materials in Road Construction using Embedded Instruments. PEAT Journal 13: 11-23.

[11] Couth, R., Trois, C., Parkin, J., Strachan, L.J. and Wright M. (2011) Delivery and viability of landfill gas CDM projects in Africa-A South African experience. Renewable and Sustainable Energy Reviews 15 (1): 392-403.

[12] Dolan, P.J., Lampo, R.G. and Dearborn, J.C. (1999) Concepts for reuse and recycling of construction and demolition waste. USA Construction Engineering Research Laboratories Technical Report 99/58.

[13] European Environmental Agency (EEA) (2002) Review of Selected Waste Streams. Technical Report N.69 , European Environmental Agency, Copenhagen, Denmark.

[14] Franklin Associates (1998) Characterization of building-related construction and demolition debris in the United States, Prepared for The U.S. Environmental Protection Agency Municipal and Industrial Solid Waste Division Office of Solid Waste, Report No. EPA530-R-98-010.

[15] Huang, W.L., Lin, D.H., Chang, N.B. and Lin, K.S. (2002) Recycling of construction and demolition waste via a mechanical sorting process. Resources, Conservation and Recycling 37 (1): 22-37

[16] Greater Johannesburg Metropolitan Council (2000) Report on interactive Planning Workshop for Johannesburg. In World Bank, Upgrading Urban Communities. Available from http://web.mit.edu/urbanupgrading/upgrading/case-examples

[17] Inyang H. (2003) Framework for Recycling of Wastes in Construction. Journal of Environmental Engineering 129: 887–898

[18] Klang, A., Vikman, P.A. and Brattebo, H. 2003. Suistanable management of demolition waste – an integrated model for evaluation of environmental, economic and social aspects. Resources, Conservation and Recycling 38 (4): 317–334

[19] Kourmpanis, B., Papadopoulos, A., Moustakas, K., Stylianou M., Haralambous K.L. and Loizidou, M. (2008) Preliminary study for the management of construction and demolition waste. Waste Management & Research 26 (3): 267–275

[20] Leite, F.C., Motta, R.S., Vasconcelos, K.L. and Bernucci, L. (2011) Laboratory evaluation of recycled construction and demolition waste for pavements. Construction and Building Materials 25 (6): 2972–2979

[21] Macozoma, S.D. (2006) Developing a self-sustaining secondary construction materials market in South Africa. A dissertation submitted to the University of the Witwatersrand, to fulfill the requirements for the degree of Master of Science in Engineering. Faculty of Engineering and the Built Environment. Johannesburg, South Africa. University of the Witswatersrand

[22] Marlow A. T. (2011) The Waste Hierarchy http://andrewtmarlow.wordpress.com/2012/05/15/waste-hierarchy/

[23] South African Council for Scientific and Industrial Research, Committee for State Road Authorities, Highway Materials Committee, Materials Testing Subcommittee, National Institute for Transport and Road Research (1986) Technical Methods for Highways TMH1- Standard Methods of Testing Road Construction Material. Pretoria: National Institute for Transport and Road Research.

[24] Department of Natural Resource Preventing Pollution at Rock Quarries, Missouri (2008) A Guide to Environmental Compliance and Pollution Prevention for Quarries in Missouri.

[25] Municipal Demarcation Board, South Africa. (2008). from http://www.demarcation.org.za/

[26] Paige-Green, P. and Ware, C. (2006) Some material and construction aspects regarding in situ recycling of road pavements in South Africa. Road Material Pavement 7 (3): 273–287

[27] Pashoalin, R. F., De Carvalho, A. C. and Barroso Castanon J. A. (2012) Construction and Suitable Development of Recycle and Demolition Waste. 28th Conference, Opportunities, Limits & Needs Towards an environmentally responsible architecture Lima, Perú

[28] Poon C.S., Management of construction and demolition waste. (2007) Waste Management 27 (2): 159-160

[29] Community Survey. (2007). Basic Results: Municipalities. Pretoria: Statistics South Africa. Available from: http://www.statssa.gov.za/Publications/P03011/P030112007.pdf

[30] Vegas I., Ibañez, J.A., San José, J.T. and Urzelai, A. (2008) Construction demolition wastes, Waelz slag and MSWI bottom ash: a comparative technical analysis as material for road construction. Waste Management 28(3): 565-74

[31] Montecinos, W. and Holda, A. (2006) Construction and demolition waste in Denmark, Example of brick, wood, treated wood and PVC management. Available from: *cowam.techh.net/Denmark_CD_Waste.pdf*

[32] Tadesse, D. (2010) The impact of climate change in Africa. Pretoria: Institute of Security Studies.

[33] Wang, J. Y., Touran, A., Christoforou, C. and Fadlalla, H. (2004). A system analysis tool for construction and demolition waste management. Waste Management 24 (10): 989–997

Chapter 4

4 Durability and properties of C&D materials for road construction

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Abstract

The properties of Construction and Demolition (C&D) waste change according to its original components and construction or demolition techniques. Main disadvantages in the application of C&D wastes are heterogeneity, which can be reduced using specific techniques of sorting process, and indexes of durability lower than for other natural aggregates commonly used.

The present research investigated the possibility of replacing natural aggregates in road applications with rubble derived from the deconstruction of buildings in South Africa. Laboratory tests were conducted in order to assess chemical and geotechnical properties of concrete and masonry recovered and of a specific mix of these two.

These materials were investigated following procedures used for natural materials in road design. The results obtained for C&D waste meet the requirements for using in unbound granular layers according to AASHTO and South African design criteria.

The issues related to durability were largely studied in this paper. The investigation results show a clear correlation between water absorption and percentage of fine lost under stress application. The low variation of the C&D long term strength characteristics and the null environmental risk of using recycled materials were also positively reported in this research.

Based on these results, the use of C&D waste is strongly suggested for unbound granular road bases.

4.1 Introduction

In the road industry, Construction and Demolition (C&D) waste is normally considered suitable for construction due to the good geotechnical characteristics, chemical stability and other benefits to the environment (Wahlström et al., 2000). However, these parameters should be always verified before its use because the properties of C&D waste depend on the constituent materials and on the techniques of construction and demolition of the generating structures (Kourmpanis et al 2008).

The C&D waste generally consists of 90% between crushed concrete and bricks (Hendriks and Jassen, 2001) but it is also made of mortar, natural rocks and lightweight masonry materials.

The demolition process usually produces rubble that is an unsorted mixture of different elements of the original structure. At the base of the strong heterogeneity is the high cost and complexity of separating the constituting components (Angulo et al, 2003). The application of processes such as the selective sorting method would encourage and simplify the reuse or recycling of this waste (Poon et al. 2001). This method allows the separation at the main component, main materials present in small percentages are then separated in the sorting centers (Huang et al, 2002). The selective sorting process is long and complex. It can be replaced by means of the deconstruction which is the demolition technique that consists of the selective dismantling of civil structures for reusing or recycling purposes (Hobbs and Hurley, 2001). This methodology considers the selective demolition of homogeneous building components, minimising mixing during the demolition process. The result provides a considerably more homogeneous waste and materials such as concrete and red bricks, which are suitable for road construction, are ready for being used (Poon et al, 2001).

It is also unlikely, but possible, that waste contains toxic components (Reeves et al, 2007) which could, if landfilled or used unmodified in road construction, have deleterious effects on the environment. For this reason the examination for the presence of hazardous components are always suggested when recycled materials may come in contact with water (Roussat et al 2006).

The C&D materials are generally appropriate for the production of non-cohesive construction aggregates (Rombi et al, 2010) due to their good geotechnical properties (Hendriks F. and Jassen, 2001) although there are some characteristics that are different from natural materials. The maximum dry unit weight of C&D aggregates ranges from 14 to 21 kN/m^3, the optimum moisture content is between 10% and 14.6% (Barbudo et al, 2012) and water absorption is often higher than 12% (Leite et al, 2011). Aggregate Crushing Values (ACV) observed between 34 and 65%, and Los Angeles Abrasion test (LAA) between 30 and 72% (Gopala et al, 2010).

The application of C&D waste alone in a road layer requires deep knowledge for establishing specific operative range of values and test methods for assessing its properties. In fact, proper classification for the C&D waste is still in developing stage (Angulo and Mueller, 2009), for this reason the systems currently in use are those made for natural soils/aggregates. The American Association of State Highway and Transportation Officials (1982) classification system and the Unified Soil Classification System (USCS) (Casagrande, 1948) are the most common geotechnical classification, which are based on the particle-size distribution and Atterberg limits. In South Africa a more complex soil classification has been developed for applications in road construction which also takes in to account flakiness index, strength, swell and durability (COLTO, 1998). Materials are classified as crushed stone, named G1 G2 G3, crushed/natural gravel, G4 G5 G6, and gravel/soil, G7 to G10 (Committee of State Road Authorities. 1985).

The comparison of the AASHTO and SA classifications methodologies is not direct or simple. It could be said that the crushed rocks G1, G2, G3 and natural gravel G4, which have a specific grading envelope and Plasticity Index (PI) less than 6, can be compared to A1 group in AASTHO classification. The natural gravel G5 is similar to A2 and soils from G6 to G9 fall in A4 or A5 categories. Clayed soils (such as A6 and A7) are not considered in South African soils classification.

The C&D waste should be studied better for understanding all its aspects and for finding solutions to its common issues. This research presents the efficacy of deconstruction to prevent contamination by hazardous materials and reduce its heterogeneity; in particular a study on the durability for the long-term behaviour was carried out. The geotechnical properties of the C&D waste produced by the deconstruction of an ex-military area, the Natal Command, in Durban, South Africa, are studied. Concrete and masonry, produced by the demolition of walls and foundations and a blend of these two materials were tested as per the South African specifications. These analyses are accompanied by additional tests that help better understanding of the long term engineering behaviour of this material in real applications.

Though some of the results exceeded the limits fixed for natural aggregates, the results did not change significantly when the tests were performed in dry or wet condition or after wet-dry cycles. It means that the behaviour of the C&D aggregates is not much affected by the presence of water. A correlation between water absorption and Los Angeles Abrasion (LAA) value and with Aggregate Crushing Value (ACV) was also observed. This relationship, which links physical and mechanical properties, could be used for prediction of the future behaviour of an aggregate based on its water absorption.

4.2 Materials and Methods

The following sections present the details of the source of C&D waste material, the steps followed to prepare the specimen and the various laboratory tests carried out in this study.

4.2.1 The Natal Command and its deconstruction

The materials used in this research came from the property commonly known as the Natal Command, which was a group of about 70 buildings in 21ha on the Durban beachfront. The buildings were ruined with often missing pieces (finishing) as shown in Figure 4-1. The typical structure of deconstructed buildings of the complex was only one floor composed of unreinforced concrete foundations, unreinforced concrete floor slabs and patios, single clay brick wall to windowsill, half clay brick wall to roof, concrete roof beams, timber roof trusses and corrugated asbestos cement roofing.

Figure 4-1 Typical building of Natal Command

The varieties of materials which constituted each individual building would have given an extremely heterogeneous product if it was not reduced by adopting the selective deconstruction process carried out by Atomic Demolishers (Pty) LTD in April 2011. Trusses were removed first then all wood parts were removed. Asbestos cement roof sheeting had a special treatment due its specific hazardous nature. Walls and floors, then, were separately demolished by excavators in two different stages. Figure 4-2 shows the procedure that had been followed.

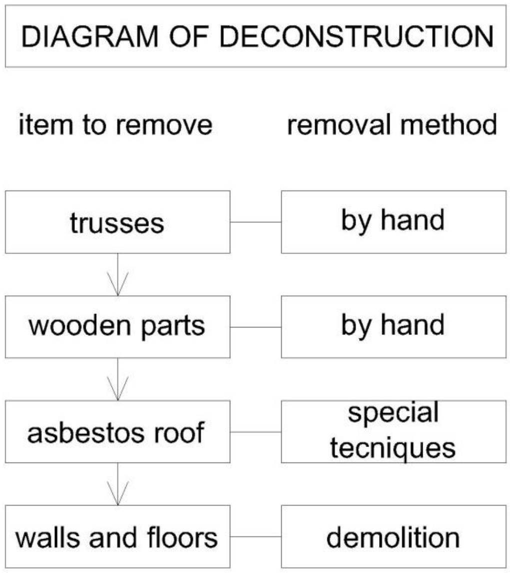

Figure 4-2 Diagram of deconstruction

The rubble produced by this demolition generated concrete (from floors and foundations) and clay bricks and mortar (from walls) which are named masonry for simplicity. These materials were tested as aggregates for road construction.

4.2.2 Material preparation

Concrete and masonry were deposited in a designated area in two separated stockpiles. While the material was dumped, it was essential to avoid contamination at the site and minimise segregation and dust by adding water.

The use of materials in road pavements requires specific grading for good contact between the particles; for this reason appropriate machines were involved to reduce the rubble to aggregates. Figure 4-3 shows the procedure followed by means of the combination of a pecker (ATLAS COPCO - SB10), a screener (Atlas Copco HCS 3715) and an impact crusher (Atlas Copco PC1060). The crusher was set to give a grading curve that falls within G1\G2\G3 envelope. Concrete and masonry were prepared separately then stockpiled for testing or blending.

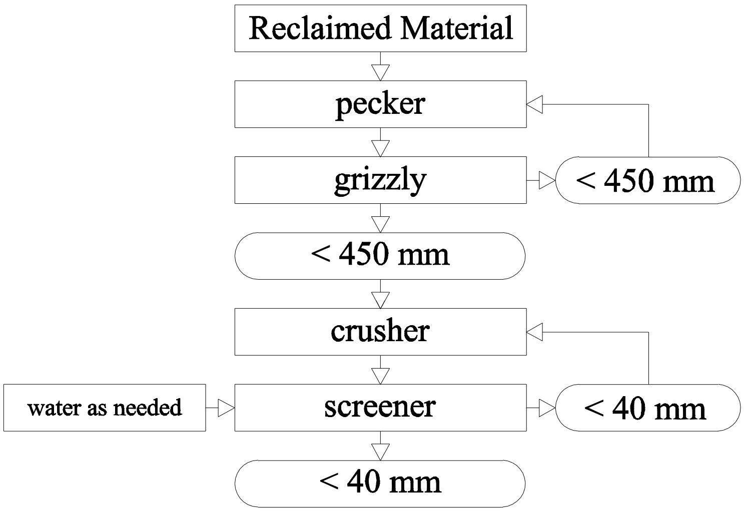

Figure 4-3 Screening and crushing procedure

A blend was then produced by mixing 25% of concrete and 75% of masonry by volume, to match the proportions of these materials roughly produced by demolition of buildings in the Durban Metropolitan Area (DMA). The blend was prepared in the storage area through a payloader mixing together three buckets of concrete with nine buckets of masonry, and by adding water to keep the fines within the mixture. Figure 4-4 shows a picture of each material tested in this research.

Figure 4-4 Crushed concrete, masonry and blend materials

4.2.3 Laboratory tests

The knowledge of mechanical-physical and geo-environmental characteristics is indispensable in anticipating the difference in behaviour of the C&D waste from the natural aggregate. In this study, the two materials produced in the crushing process viz. concrete, and masonry and the blend obtained by mixing the two materials were analysed in order to assess their suitability for road construction. Table 4-1 shows the tests performed and the number of specimens tested.

Table 4-1 Tests performed in this research

TESTS	CONCRETE	BLEND	MASONRY	TOTAL
Specify Gravity and Water Absorption retained 4.75 mm	5	5	5	15
Specify Gravity and Water Absorption passing 4.75 mm	5	5	5	15
Sieve analysis	5	5	5	15
Atterberg limits	1	1	1	3
Compaction test	5	5	5	15
California Bearing Ratio	5	5	5	15
Flakiness Index	1	1	1	3
Aggregates Crushing Value	2	2	2	6
Aggregates Crushing Value (wet-dry cycles)	2	2	2	6
Los Angeles abrasion Test	5	5	5	15
Durability Mill Index	1	1	1	3
CD Triaxial test	-	3	-	3
TOTAL	37	40	37	120

The specifications followed for each test are shown in Table 4-2. Except for tests identified in text, the specifications followed are the "TMH1– Standard Methods of Testing Road Construction Materials" (TMH1, 1986) of South Africa.

Table 4-2 List of tests performed and specifications used

TESTS		METHOD
Geotechnical properties	Specify Gravity and Water Absorption retained 4.75 mm	TMH1-B14
	Specify Gravity and Water Absorption passing 4.75 mm	SANS 3001-AG21:2011
	Sieve Analysis	TMH1-A1
	Atterberg Limits	TMH1-A2 and A3
	Compaction	TMH1-A7
	California Bearing Ratio	TMH1-A8
	Flakiness Index	TMH1-B3T
	Aggregates Crushing Value	TMH1-B1
	Aggregates Crushing Value (wet and dry cycles)	Modified PA test method no 519
	Los Angeles Abrasion	SABS 846
	Durability Mill Index	Sampson and Roux, 1987
	Consolidated Drained Triaxial	ASTM D7181 – 11
TESTS		**EQUIPMENT**
Chemical and crystallographic properties	X-ray diffraction	Panalytical Empyrean X-ray Diffractometer
	Microscope evaluation	LEO 1450 VP SEM
	Leaching test	Perkin Elmer, Optima 5000 Series

4.2.3.1 Mineralogical properties

The crystal structure of a mineral is usually studied by x-ray diffraction, a non-destructive analytical technique. X-ray diffraction patterns were obtained with a Panalytical Empyrean X-ray Diffractometer at the Geology Division of the School of Agricultural, Earth and Environmental Sciences of UKZN, using Co Kα radiation (1.79 Å). The scan was taken from 3 to 90 degrees 2-theta, with a step size of 0.008 degrees and an integration time of 7 seconds per step. Data interpretation was done using the Panalytical proprietary software Highscore+.

In the Mechanical Engineering Laboratory, the three materials were also analysed by means of a scanning electron microscope (SEM). This investigated the atoms composing the substance by scanning the sample through beam of electrons.

4.2.3.2 Chemical tests

The knowledge of the chemical characteristics is essential to assess the environmental risks of a recycled material. Different countries have already issued specific legislations, but to date not in South Africa, for the investigation of hazardous substances which could be released by the reclaimed C&D waste in the environment. In this research, samples were tested following the standards suggested by the European Community (EN 12457-2) for obtaining the eluates and additional laboratory tests on these to check the presence of hazardous elements.

C&D waste is not a natural material and could release hazardous constituents into the environment, especially in presence of water. For this reason, before their civil engineering use, tests for determining the pollution potential have to be combined to the standard geotechnical analysis.

The European Community issued the EN 12457-2, a procedure developed for finding hazardous elements in the eluates. In fact, the greatest risk is when the water filters through the recycled material possibly leaching pollutants into the ground water and in the surrounding environment. Samples of particles sizes passing 4 mm sieve were prepared and mixed with water in a liquid\solid ratio of 10 l\kg. At a constant temperature of 20°C the mixture was agitated in a bottle for 24 hours to simulate the percolation. The liquid part was, then, separated and tested by the environmental laboratories of Civil Engineering, UKZN. The observation of the substances present in concrete, masonry and blend eluates was carried out by means of the Inductively Coupled Plasma (ICP) equipment.

4.2.3.3 Geotechnical tests

The geotechnical laboratory tests evaluated the properties of concrete, masonry and blend. The tests procedure are the same in use for natural aggregates and soils. The tests were performed in the geotechnical laboratory of University of KwaZulu Natal (UKZN) with the exception of Los Angeles Abrasion test, which was carried out in the laboratory of the eThekwini Municipality, and the Durability Mill Index in the Soilco Materials Investigations (Pty) Limited laboratory in Pinetown. All results obtained were compared with the limits suggested by the COLTO classification attached in Appendix B.

4.2.3.3.1 Determination of specify gravity and water absorption

Specific gravity and water absorption of materials were determined following the test methods TMH1-B14 and SANS 3001-AG21:2011. Different test procedures are used for the fractions larger and finer than 4.75mm. Water absorption is one of the main characteristics of C&D material that affects the amount of water necessary for compaction and the durability.

4.2.3.3.2 Particle size distribution analysis

The C&D waste aggregates were prepared during the crushing, screening and mixing procedure as shown in Figure 2 to fall within G1-2-3 grading envelope of COLTO.

4.2.3.3.3 Atterberg Limits

The liquid limit, plastic limit and plasticity index were determined through methods A2 and A3 of the THM1. This group of tests investigates the plasticity of the materials passing 0.425 mm.

4.2.3.3.4 Compaction test

The TMH1 compaction test method-A7 was followed on specimens with particle size smaller than 19mm using a modified methodology developed by the AASHTO for determining the bearing characteristics of the typical Class 2 aggregate base (Theyse, 2002)

4.2.3.3.5 Californian Bearing Ratio (CBR)

The California Bearing Ratio (CBR) test was also performed on the materials passing the 19mm sieve. Specimens were compacted at OMC using varying compactive efforts as suggested by TMH1 and were tested in soaked condition. The CBR value, which indicates the strength of a material, was interpolated for 98% modified AASHTO density, by determining the bearing ratios at the different densities.

4.2.3.3.6 Flakiness Index

The flakiness index of coarse aggregate is used to determine the percentage of flaky aggregates. The spherical shape of an aggregate allows obtaining an appropriate packing without applying excessive energy in compaction. In accordance to South African standard, the test is performed on three different size ranges.

4.2.3.3.7 Durability Tests

A series of durability tests have been performed. These are not only important for the South African classification, but for the applicability and workability of C&D waste materials in general. In fact these tests describe the ability of the aggregates to withstand the environmental and mechanical degradation during construction and service period of the aggregates. The tests are split in two typologies for simulating the mechanical stress and weathering behaviour.

Los Angeles Abrasion (LAA) test and Durability Mill Index (DMI) assess the durability of materials by means of its abrasion, Aggregate Crushing Value (ACV) considers strength aspect.

The universally recognised LAA test is the most common test to evaluate toughness, strength and abrasion characteristics. In Europe is largely use and it has a proper limits for natural and C&D materials. This test followed the South African specification SABS 846 although it is not a requirement of COLTO for sub-layerworks.

The standard South African tests for assessing the durability of an aggregate are the 10 per cent Fines Aggregate Crushing Value (10% FACT) and ACV for G1 G2 or G3 materials, while DMI is used for G4 materials. The inability to perform the test 10% FACT due to limited sample available sizes led to the use of the related test, the Aggregate Crushing Value (ACV), which also defines the strength. The two tests have a direct correlation when ACV is between 14 and 30 and the 10%FACT range from 300 to 100 kN (Alexander and Mindess, 2005).

$$\text{ACV} = 38 - 0.08 \times 10\%\ \text{FACT}$$

The ACV test followed the specification included in TMH1 method B1 which assesses the behaviour of the aggregates under compression in dry or wet conditions.

The Durability Mill Index (DMI) follows the recommendation of Sampson and Roux (1987). In this non-standard abrasion test the sample is split in 4 sub-samples, named A, B, C, and D based on the size of the aggregates. Sub-sample A is prepared in order to determine the plasticity indexes by means of the Atterberg’s methodology. The abrasive resistance of the remaining sub-samples is investigated under wet and dry conditions inside the Durability Test Machine. As shown in Figure 4-5, the testing equipment is similar to the more common LA Abrasion Test Machine.

Figure 4-5 Durability Mill machine

For a better understanding of the C&D waste durability properties in long term due to weathering conditions, a modified ACV was performed, with the samples undergoing ten wet-dry cycles. Each cycle took 24 hours, 17 hours for the sample to be kept in soaked condition and 7 hours in an oven at 60°C as suggested by Pennsylvania PA test method no 519.

4.2.3.3.8 Consolidated Drained Triaxial Test

Consolidated drained (CD) triaxial tests were carried out on samples of blend material so as to complete its geotechnical characterization. These tests were carried out to obtain the shear strength characteristics of the material which are required for the analysis of slopes in view of its practical applications for road construction. Angle of friction and cohesion are calculated and compare with the standard classified granular material used in South African road pavements.

The blend material was sieved and the maximum particles dimension was set to 19 mm as for other tests. This enabled the triaxial sample size of 100 mm diameter and 200 mm length to have an acceptable ratio of maximum size of aggregates to specimen diameter ratio close to 1/5. The specimen was prepared at compaction equal to 100% of modified AASTHO and then saturated.

4.3 Results and discussions

4.3.1 Mineralogical properties

4.3.1.1 X-ray diffraction (XRD)

Figure 4-6 shows the diffraction patterns on samples passing 4.75 mm. The three materials have quartz as their dominant crystalline constituent, angle position (2theta) = 31°, and other phases present in very minor amounts. Among the minor constituents, Calcite is present in all samples, while very minor Magnesite in the masonry and Feldspar in concrete and blend.

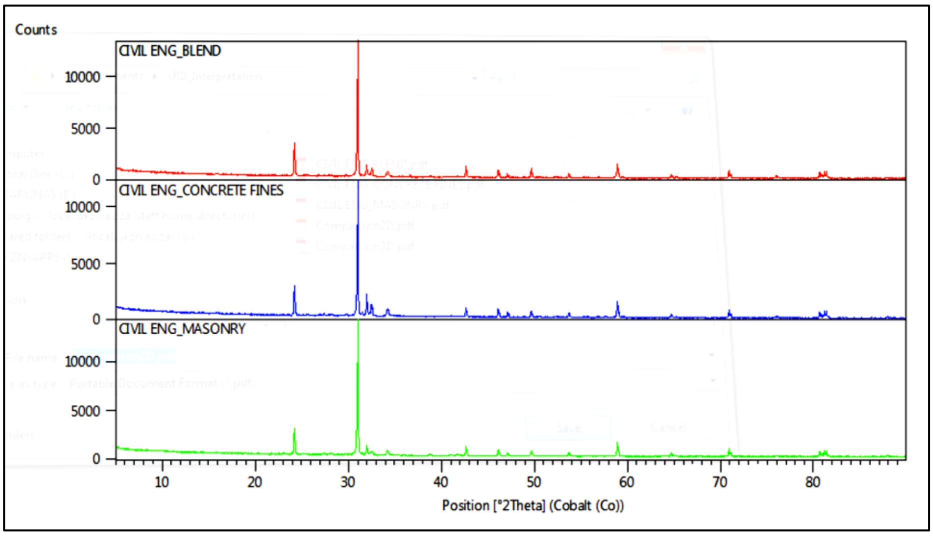

Figure 4-6 XRD diffraction patterns

4.3.1.2 The Scanning Electron Microscopy (SEM)

The fraction of each sample passing 4.75 mm was mainly composed of Oxygen, Silicon, Calcium and Carbon as shown in Figure 4-7, 4-8 and 4-9 while other elements, such as magnesium, iron, potassium, aluminium and titanium, were only found in minor amounts.

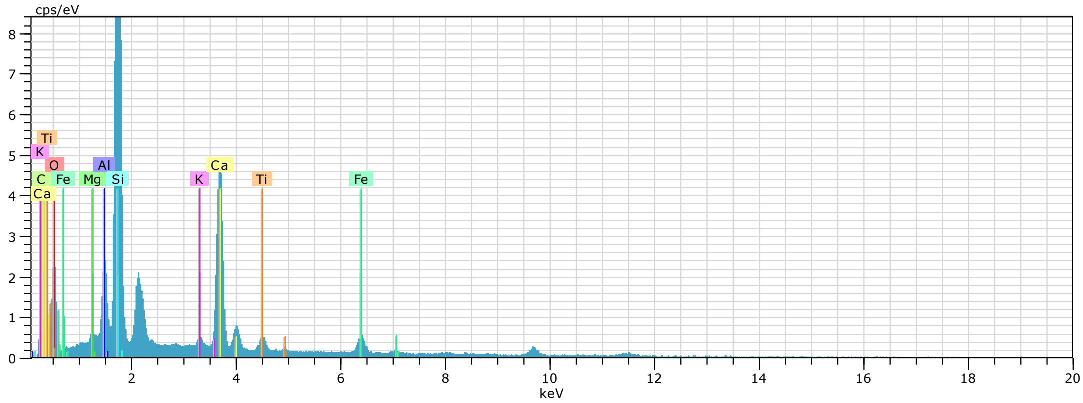

Figure 4-7 Concrete SEM results

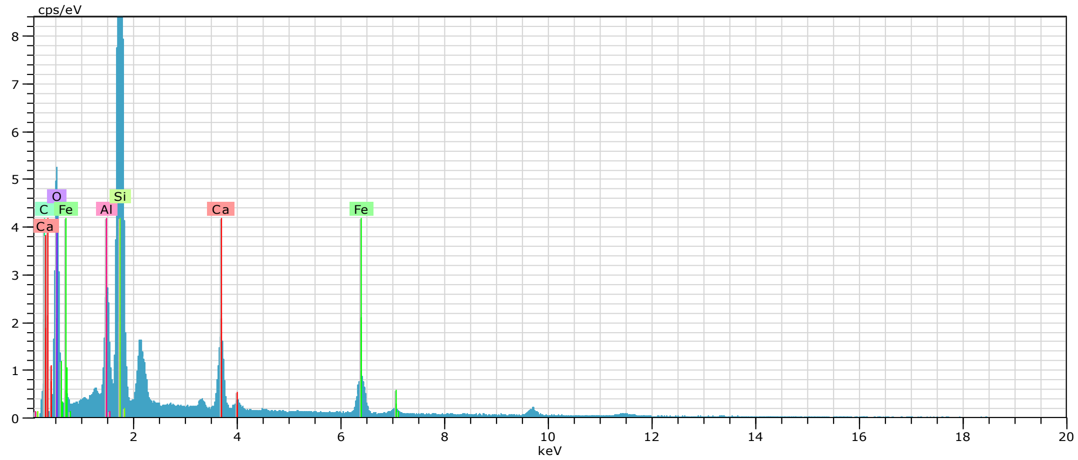

Figure 4--8 Masonry SEM results

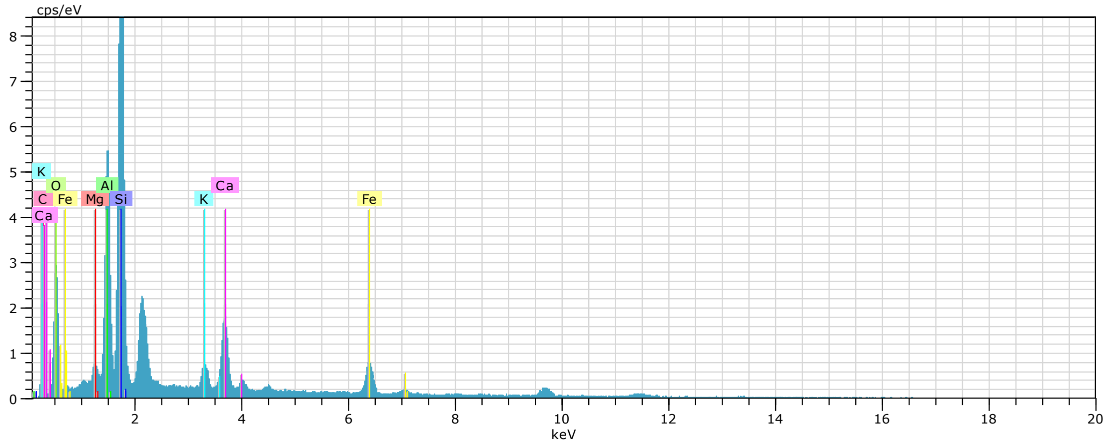

Figure 4-9 Blend SEM results

4.3.2 Chemical proprieties

4.3.2.1 Leaching test

The results are shown in Table 4-3. It is observed that none of the materials tested contains hazardous elements which exceed the limit values indicated, as specified in 2003/33/EC. This test validated the reuse of concrete, masonry and a blend of them as aggregates for road construction from in terms of environmental concerns.

Table 4-3 Hazardous content in concrete, masonry and blend in (mg/l)

Material	Zn	Cr	As	SO_4	Pb	Cu	Mo	Sb	Ba	F
CONCRETE	0.024	0.099	0.018	-	0.025	0.042	0.042	0.081	0.076	-
BLEND	0.024	0.042	0.023	-	0.029	0.040	0.043	0.099	0.112	-
MASONRY	0.021	0.036	0.019	-	0.023	0.037	0.041	0.081	0.091	-
Limit values	1.2	0.1	0.06	1500	0.15	0.6	0.2	0.1	4	2.5

4.3.3 Geotechnical properties

4.3.3.1 Specific Gravity and water absorption

Table 4-4 shows the values of specific gravity and water absorption for coarse aggregate material (retained on 4.75 mm sieve). The specific gravity is similar to that of natural aggregates which is reported as 2.7 and commonly used for base layer (Araya, 2011).The water absorption of these materials is higher than the corresponding value for natural aggregates. The specify gravity is more or less the same for all the three materials despite masonry having water absorption more than 28% as compared to concrete material.

Table 4-4 Specify gravity and water absorption for coarse aggregates (retained on 4.75mm)

Material	Specific Gravity		Water Absorption	
	mean	standard dev.	mean	standard dev.
CONCRETE	2.623	0.016	5.56%	0.28
BLEND	2.582	0.015	6.86%	0.22
MASONRY	2.582	0.073	7.14%	0.36

The water absorption and specific gravity values obtained for fine aggregate material (passing 4.75 mm sieve) are shown in Table 4-5. The density is not significantly affected by the particle sizes while the results of the water absorption indicate a significant rise for all three materials. Coarse concrete composed mostly of aggregates and the fine concrete material mainly cement which increased the water absorption by 75%. Masonry, which is a more homogeneous material made up by clay bricks and mortar, indicated an increase in the water absorption by 25% for fine fraction. Blend, which is a proportion of the two materials mixed together, follows similar trend.

The tests conducted on finer particles of concrete for determining the water absorption show a high deviation from the average due to the poor reproducibility of the procedure using the cone method.

Table 4-5 Specify gravity and water absorption for fine aggregates (passing 4.75mm)

Material	Specific Gravity		Water Absorption	
	mean	standard dev.	mean	standard dev.
CONCRETE	2.688	0.071	9.44%	1.05
BLEND	2.630	0.024	9.34%	0.53
MASONRY	2.591	0.077	9.34%	0.54

4.3.3.2 Sieve analysis

The particle size distribution curves of concrete, blend and masonry, are presented in Figure 4-10. The specification indicates that the grading of a material should be within specific envelopes to allow a good packing during the compaction.

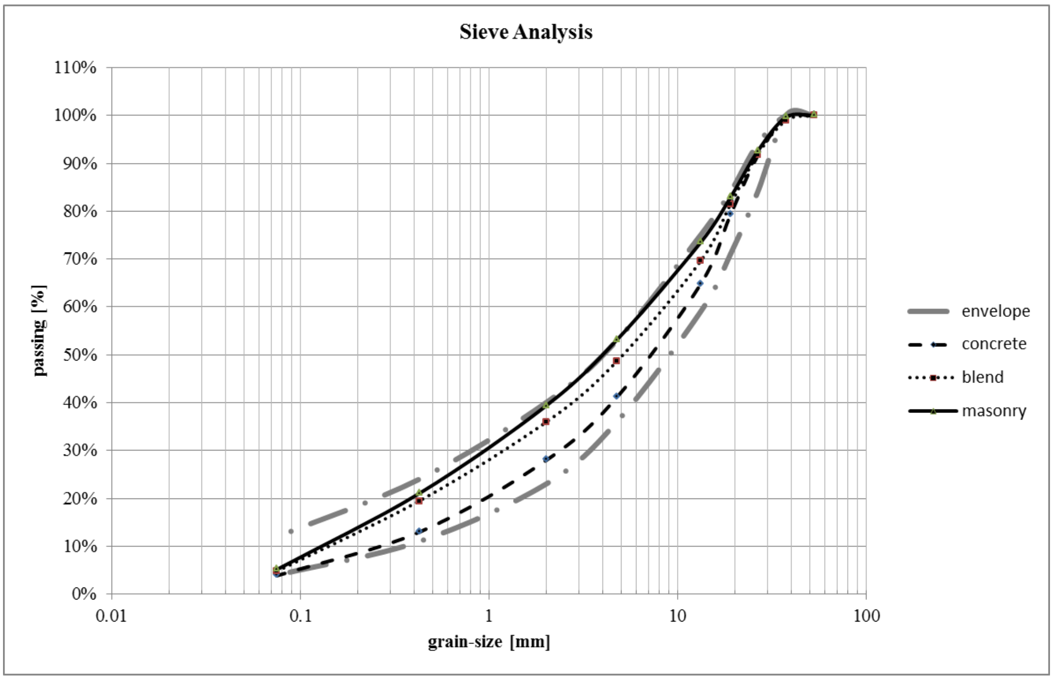

Figure 4-10 Particle size distributions

The Table 4-6 shows more clearly the particle size distributions of concrete, blend and masonry and the required COLTO envelope.

Table 4-6 particle size distributions

sieve (mm)	CONCRETE	BLEND	MASONRY	envelope
53	100.0%	100.0%	100.0%	100%
37.5	100.0%	100.0%	100.0%	100%
26.5	91.5%	91.8%	92.5%	84-94%
19	79.2%	81.4%	82.8%	71-84%
13.2	64.7%	69.6%	73.4%	59-75%
4.75	41.1%	48.6%	53.0%	36-53%
2	27.9%	35.9%	39.3%	23-40%
0.425	12.9%	19.4%	21.0%	11-24%
0.075	3.9%	4.5%	5.0%	4-12%

The values of D_{60}, D_{30} and D_{10} were measured in order to calculate the uniformity coefficient (C_u) and the coefficient of gradation (C_c), reported in Table 4-7. These values were used to classify the materials in the Unified Soil Classification System (USCS) as well graded gravel (GW), concrete and blend, or well graded sand (SW), masonry.

Table 4-7 C_u and C_c values and USCS for the three samples

Materials	C_u	C_c	USCS
CONCRETE	41.5	1.9	GW
BLEND	58.6	1.2	GW
MASONRY	53.1	1.0	SW

4.3.3.3 Atterberg limits

The test results showed no plasticity for all three types of materials. The non-plastic nature of these materials increases its suitability as a base material for road construction as it will not have swelling in the presence of water or show time dependent behaviour.

The absence of plasticity and continuously graded grading curves places all three, concrete, masonry and blend in the group A1-a in HRB classification developed by the AASHTO, which defines these as excellent aggregates for road construction.

4.3.3.4 Compaction test

The results of the compaction tests performed in laboratory are summarised in Table 4-8. All the three materials show lower maximum dry density (MDD) and higher optimum moisture content (OMC) as compared to the natural aggregates, which has MDD of 22.00 kN/m^3 and OMC of around 6% (Barbudo et al, 2012 and Araya, 2011). The highest value of MDD of 19.18 kN/m^3 was observed for concrete. The highest OMC of 13.79% was observed for masonry which had the highest water absorption value.

Table 4-8 Compaction test and CBR test results

Material	OMC		MDD		CRB values	
	mean	standard dev.	mean	standard dev.	mean	standard dev.
	%		kN/m^3		%	
CONCRETE	12.0	0.011	19.18	0.1822	114.52	12.4860
BLEND	13.2	0.011	18.72	0.2409	98.77	8.0959
MASONRY	13.8	0.013	18.70	0.2381	91.6	13.820

4.3.3.5 California Bearing Ratio

Table 4-8 shows the results of soaked CBR tests on all the three materials. Concrete gave the highest value of the CBR which is 114.52 %, and the masonry gave the smallest value which is 91.60%. All the materials tested in this study attained CBR values greater than 80% as required in the South African classification for G4 gravel (Appendix A). The minimum values of the CBR at 98% modified AASHTO density is specified for using aggregates as G4 to G9 in road layers.

4.3.3.6 Flakiness index

Aggregates with flakiness index below 35% are suitable for road construction. As shown in Table 4-9, all the three materials tested have flakiness index smaller than 13% indicating that the aggregates are of cubicle or spherical shape.

Table 4-9 Flakiness Index results

Size range [mm]	13.2 - 9.5	19 - 13.2	26.5 - 19
CONCRETE	10.13%	9.54%	5.69%
BLEND	12.87%	9.36%	10.24%
MASONRY	10.74%	8.79%	7.24%

4.3.3.7 Durability tests

4.3.3.7.1 Los Angeles Abrasion Test

The maximum allowable values for C&D materials range between 40-45% (Wu et al, 1998) depending on the layer to prevent the crushing, degradation and disintegration in long term behaviour. The results obtained are presented in Table 4-10 and as can be seen from this table, masonry does not satisfy this criterion. The standard deviation observed in the results is low for concrete and higher for masonry. The amount corresponding to the blend is in between the values for the two components.

Table 4-10 LAA test results

Material	mean	standard dev
CONCRETE	36.46%	0.34
BLEND	43.87%	1.73
MASONRY	51.07%	2.44

Concrete is a conglomerate of elements made of different resistance that after the test the weaker constituent, the cement, was polished from aggregates. The test showed that after a rapid decay, the present cement was removed leaving intact the more resistant aggregates, the strength of the material increases significantly.

4.3.3.7.2 Aggregate Crushing Value

The results of Aggregate Crushing Value (ACV), as shown in Table 4-11, establish that all the three materials exceed the limits suggested by the South African classification. However, the limit values proposed in Table 3602/3 of COLTO (Appendix A) do not specify the values for the C&D waste materials. Study like this might be used for the evaluation of specific, more realistic, restrictions. The test was performed in dry and wet conditions as per the requirements of the South African specifications. As can be seen from the table the obtained values in in dry and wet conditions did not show significant changes and the maximum difference observed is of the order of 3.45%. The results of ACV test showed greater homogeneity than those obtained in the LAA test, in fact maximum deviation was around 1%.

Table 4-11 ACV results

Material	dry		wet	
	mean	standard dev	mean	standard dev
CONCRETE	29.36%	0.29	32.07%	0.40
BLEND	35.01%	0.24	38.46%	0.75
MASONRY	36.35%	1.11	38.28%	0.04

4.3.3.7.3 Correlation with water absorption

Figure 4-11 shows the relationship between LAA value and water absorption for all the three materials tested and suggests an equation for the prediction of LAA value using water absorption value for the C&D material.

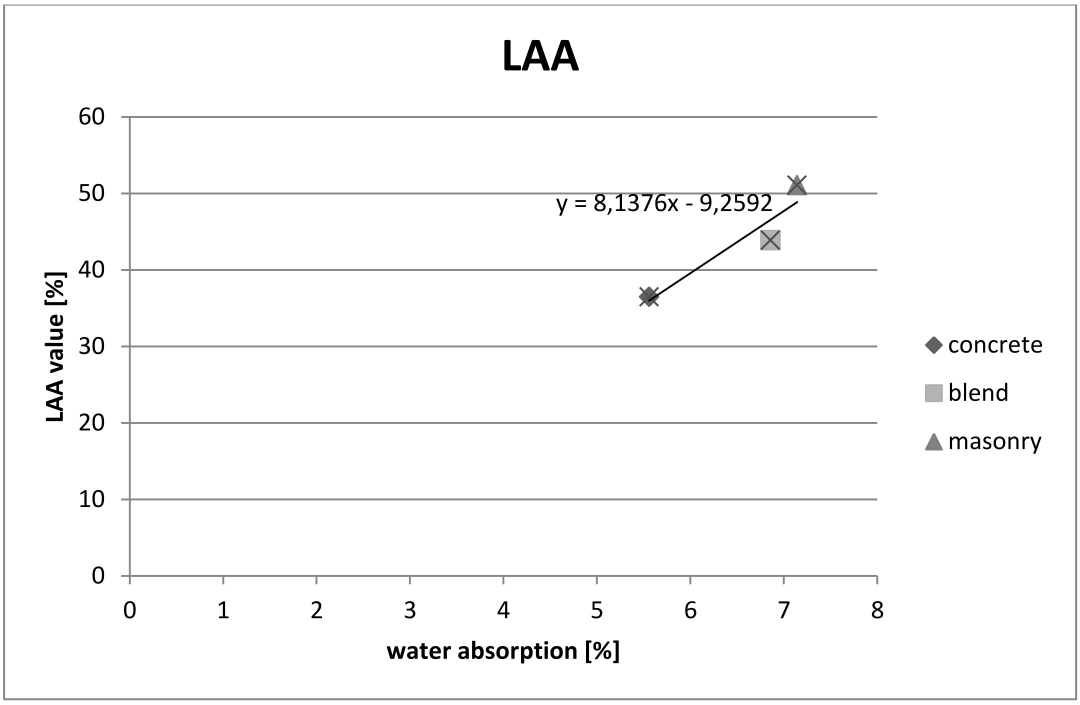

Figure 4-11 Relationship between water absorption and LAA for concrete, blend and masonry

A similar curve is plotted in Figure 4-12 for comparing other results gathered from the literature and its equation confirms that the water absorption affects the abrasion resistance of an aggregates. An aggregate with water absorption higher than 6.5% most likely gives LAA value larger than 45% which, according to the limits for C&D materials, is non-suitable for base or sub-base layers.

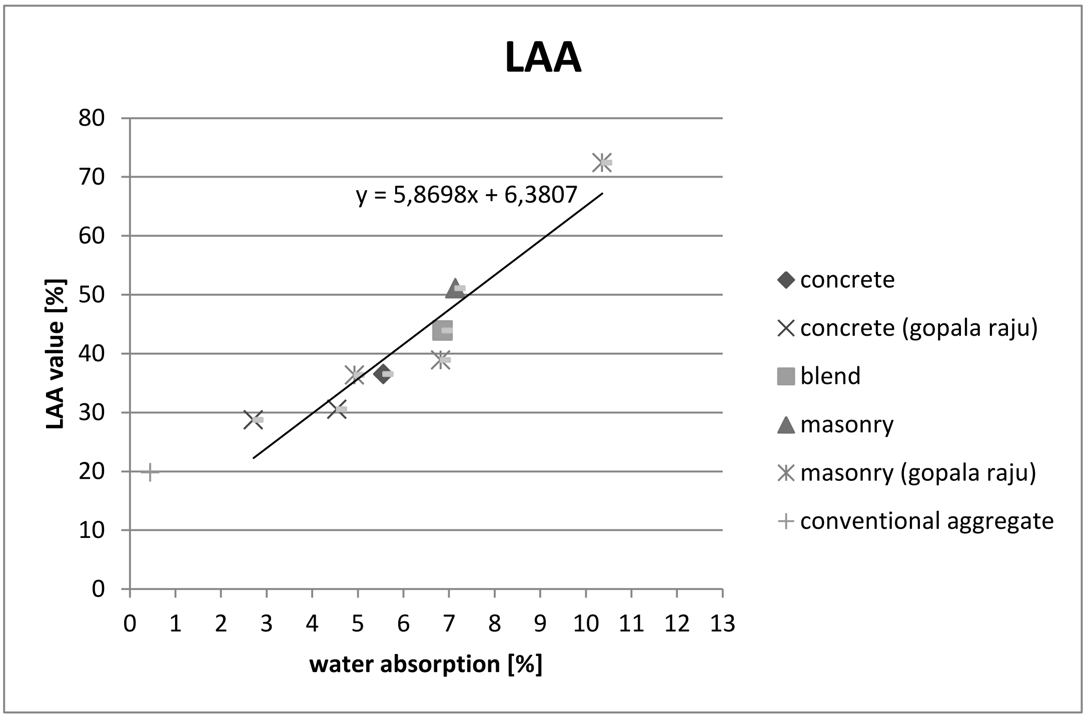

Figure 4-12 Relationship between water absorption and LAA with other results gathered from the literature

The water absorption of the test sample was also compared to the ACV achieved by the same aggregates. The comparison of results coming from the test carried out on concrete, blend and masonry permit to extrapolate a linear trend between ACV and water absorption.

Results presented in other studies were added to the results plotted in Figure 4-13. The Figure 4-14 shows, although a slight change of the trend line inclination, consistency with the results presented in this paper.

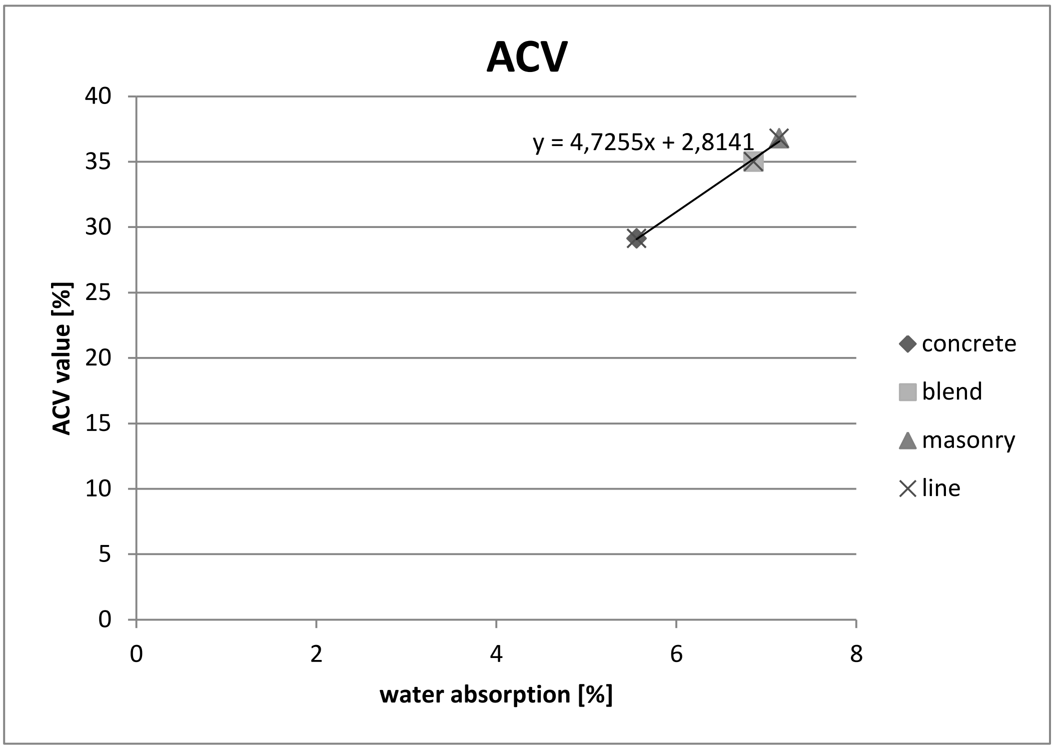

Figure 4-13 Relationship between water absorption and ACV for concrete, blend and masonry

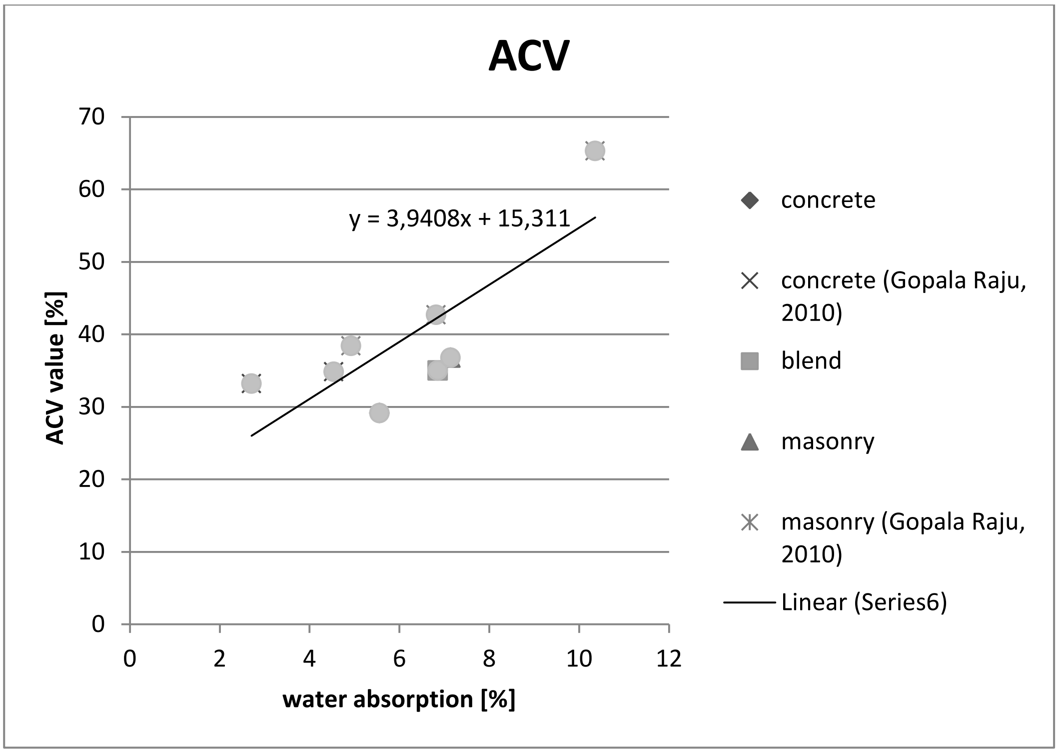

Figure 4-14 Relationship between water absorption and LAA with other results gathered from the literature

4.3.3.7.4 Weathering

The weathering studied by wet and dry cycles seem not to significantly affect the durability of concrete, masonry and blend aggregates as shown in Table 4-12.

Table 4-12 ACV after 10 wet-dry cycles

Material	dry		wet	
	mean	standard dev	mean	standard dev
CONCRETE	30.18%	0.19	31.70%	0.37
BLEND	34.92%	2.16	35.95%	1.38
MASONRY	36.10%	1.15	37.55%	0.75

The increment weight of aggregate loss after the execution of the cycles, compared to the standard test describe previously, does not exceed 1%. The graphs in Figure 4-15 and in Figure 4-16 show a sub-horizontal trend with a slight increment in ACV in all the materials. The C&D aggregates, despite the higher initial values, demonstrate a low degradation over a period of time.

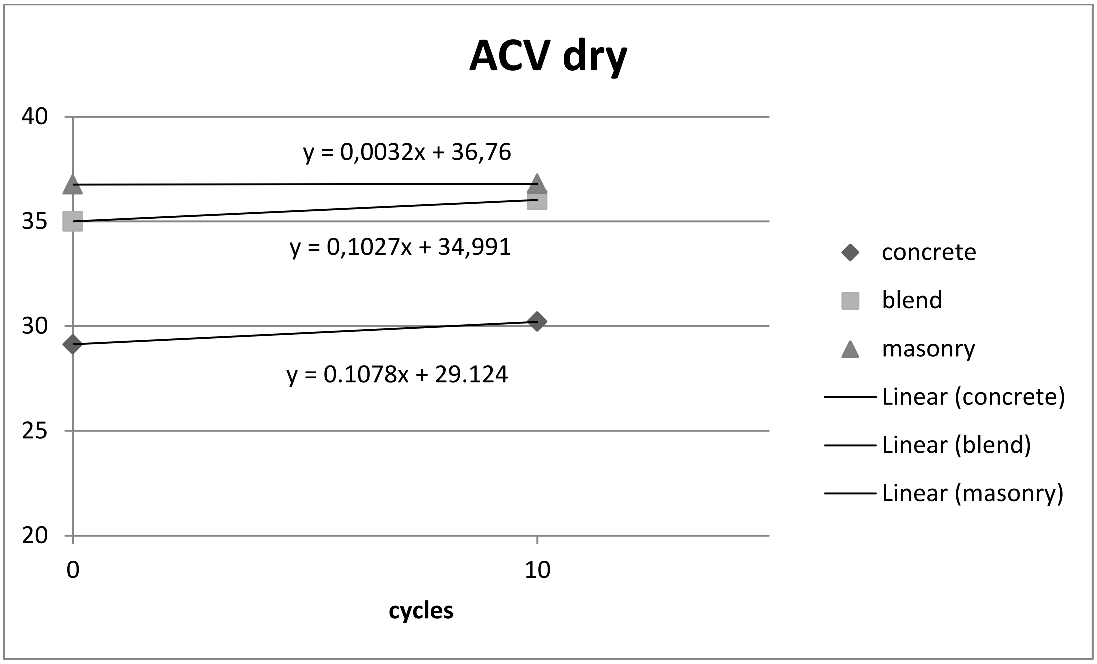

Figure 4-15 ACV dry value before and after 10 wet-dry cycles

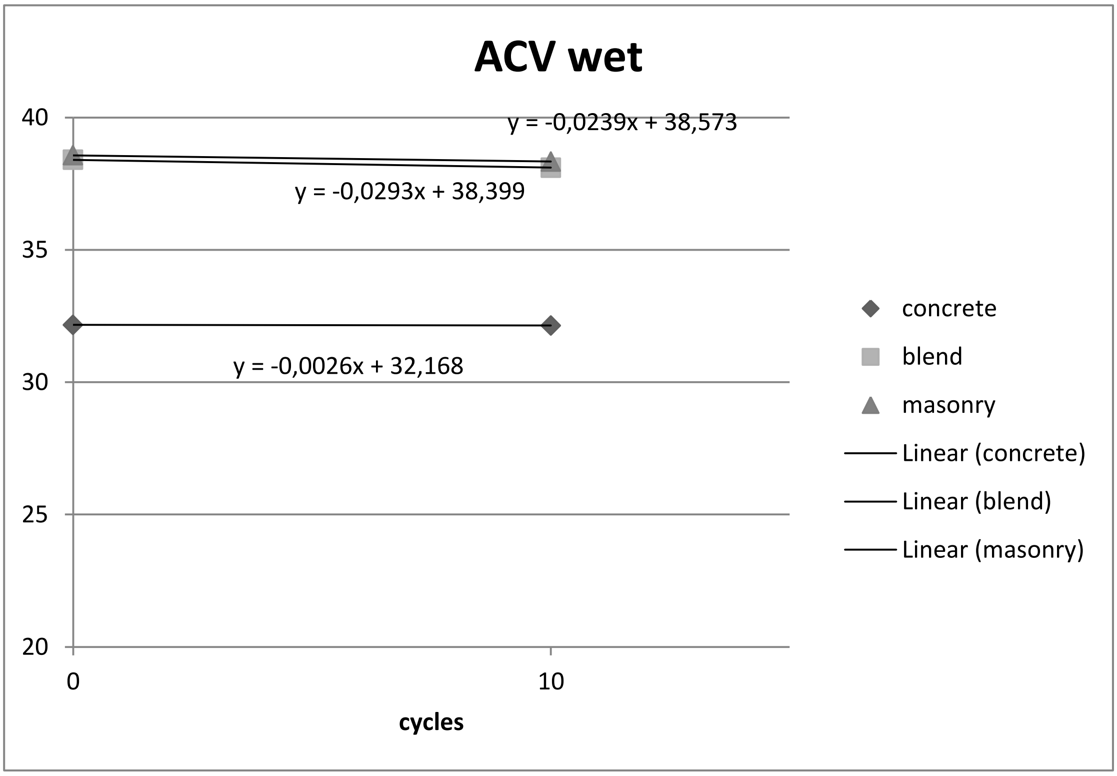

Figure 4-16 ACV wet value before and after 10 wet-dry cycles

4.3.3.7.5 Durability Mill Index

The South African classification allows the use of G4 materials that do not exceeded the value of 35% for road construction. As shown in Table 4-13, all the three materials satisfy this criterion.

Table 4-13 DMI results

Material	A	B	C	D
	plasticity	wet ball mill	dry ball mill	wet mill
CONCRETE	NP	16.54%	18.86%	16.06%
BLEND	NP	25.70%	26.41%	22.47%
MASONRY	NP	28.57%	26.61%	25.52%

4.3.3.8 Summary of standard geothecnical tests

Table 4-14 summarizes the results of the tests that have been done so far. These results are consistent with those reported in other studies such as those published by Leite et al., Barbudo et al., Araya, Gopal Raju, etc.

All the studies report concrete as it has better performance and with values more similar to natural aggregates. Specify gravity, water absorption, the optimum moisture content, the maximum dry density, the CBR and the durability tests are generally correlated. Moreover more absorption an aggregate has less is its density, its bearing and its durability. Apparently the chemical composition of the three material tested are almost the same such as reported in the mineralogical properties section. Anyhow only the passing 4.75 mm was chemical tested. The retained 4.75 mm should have the same characteristics for masonry but for concrete natural aggregates are also included.

Table 4-14 A summary of the geotechnical tests for concrete, blend and masonry

SUMMARY	CONCRETE	BLEND	MASONRY
specify gravity >4.75mm	2,623	2,582	2,582
water absorption >4,75mm	5,56%	6,86%	7,14%
specify gravity <4.75mm	2,688	2,630	2,591
water absorption <4,75mm	9,44%	9,34%	9,34%
nominal maximum size	26,5	26,5	26,5
flakiness index	<10.13%	<12.87%	<10.74%
fracturated faces	all faces are fractuated		
Grading	G1, G2, G3 envelope		
Atterberg limits	NP	NP	NP
OMC	12%	13,20%	13,80%
MDD	19,18 kN/m^3	18,72 kN/m^3	18,7 kN/m^3

CBR		114,52%	98,77%	91,60%
Durability	LA	36,46%	43,87%	51,07%
	ACV	29,36%	35,01%	36,35%
	DMI	<18.86%	<26.41%	<28.57%

These results represent a starting point for the construction of a possible classification ad hoc for this type of material or it is possible accommodate those in old classifications. The limit for each category of C&D should be developed from several experiments and test bed such as that proposed in the next chapter. If an alternative material can bear the same load of the natural material, it can be used for the same purpose and the results obtained in some tests will be used as limit value for the classification.

4.3.3.9 Consolidated Triaxial test

The results in terms of effective stresses and vertical strains ε_z at failure are summarized in Table 4-15.

Table 4-15 CD triaxial test

σ'_3 [kPa]	30	50	80
σ'_d [kPa]	479.43	651.95	970.78
σ'_d [standard dev.]	48.08	61.50	40.80
ε_z [%]	2.5	2.5	2.75

Figure 4-17 shows the axial pressure versus axial strain plot and describes the shear behaviour observed for blend material. It shows “S-shaped” curve, typical of granular materials.

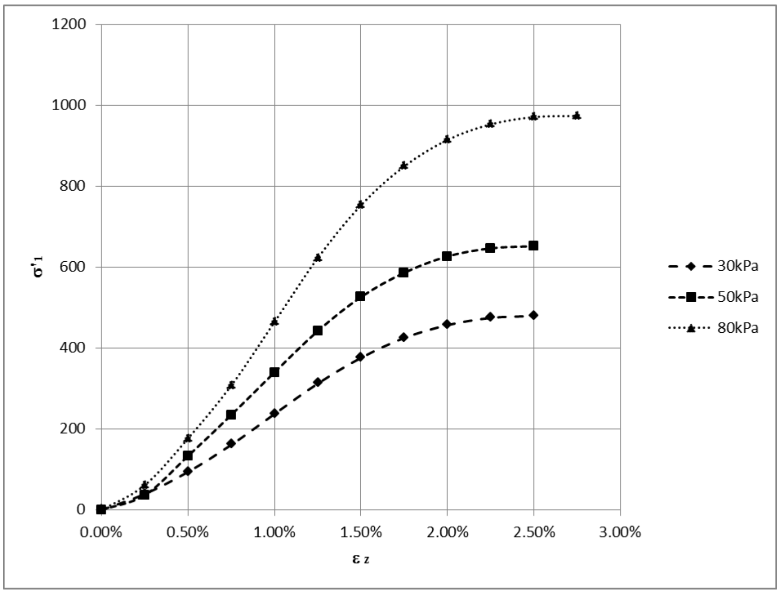

Figure 4-17 CD triaxial test results

The deformation modulus (E'), the effective internal angle of friction (ϕ') and the effective cohesion (c') were calculated on the basis of the triaxial tests results.

The Table 4-16 shows the values of the secant modulus E, obtained from the graph between σ'_1-ε_z at 50% of failure strain. It ranges from 24 .0to 48.3 MPa, depending on the confining pressure σ'_3. Different values are found in literature (Solyman, 2005 and Arundeb et al 2011) and it mostly depends on the composition of C&D materials and grade of compaction (Nierker and Sheers, 2000).

Table 4-16 Deformation Modulus of blend material

σ'_3 [kPa]	30	50	80
E' [MPa]	23.97	32.43	48.35

The results of the triaxial test are also plotted in the Lambe stress path, q'- p' diagram in Figure 4-18. This representation allows to determine the shear resistance parameters of blend, ϕ'= 51.34 ° and c'= 48.96 kPa.

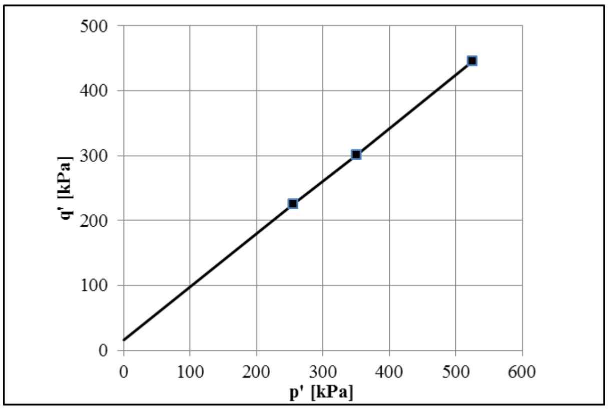

Figure 4-18 Stress path q'-p'

These values are comparable to those determined by Theyse and Muthen (2000) for G2 materials, ϕ'= 50.7 ° and c'= 38.1 kPa (Table 4-17). It is even similar with another study of granular material which has reported ϕ= 36.9 ° and c= 56 kPa (Nierker and Sheers, 2000).

Table 4-17 Angle of friction and cohesion derived by Theyese and Muthen research

material	dry		moderate		wet	
	ϕ	c	ϕ	c	ϕ	c
G1	55,01	65,04	54,55	56,34	53,82	42,97
G2	51,99	54,92	51,50	48,24	50,74	38,13
G3	50,00	50,00	49,51	43,34	48,71	33,33
G4	48,01	45,04	47,17	39,22	46,67	33,30
G5	40,89	34,39	42,34	31,75	45,17	26,34
G6	37,05	27,00	36,29	26,58	35,11	25,57

4.4 Conclusions

In this research, the C&D waste material derived from the dismantling of buildings in an ex-military area in Durban was studied for assessing its potential as aggregate for road construction. The deconstruction of buildings and the processing at the collection site allowed the production of reasonably homogeneous rubble, clean from impurities such as wood, metal, glass and cardboard. Three derived construction materials were studied, the first was mostly concrete, the second one clay brick masonry and the third one was a blend of these two obtained by mixing the first two. Mineralogical studies on three materials indicated that all the samples contain quartz as the predominant mineral and contain Calcite and Feldspar in small quantities. The chemical analysis carried on the leachate collected from all the three materials, demonstrated the absence of hazardous components, in term of the potential environmental impact, in terms of concentrations prescribed by the EU standards. As such, no additional rehabilitation treatment is required on these materials before their use in the field.

The geotechnical tests carried out demonstrate that concrete, masonry and blend are good, non-plastic materials, suitable for construction of base or sub base road layers. The applicability in road construction was verified by laboratory tests that classified them as A1-a as per the HRB classification and as G4 according to the South African COLTO classification. Concrete and blend were classified as GW while masonry as SW according to the USCS.

The high water absorption was confirmed to be a typical characteristic of C&D waste. It was observed that water absorption significantly affected the optimum moisture content and the durability showing higher loss of weight percentage than natural aggregates. In particular, results show a direct correlation between water absorption with Los Angeles Abrasion test and with Aggregate Crushing Value, which is useful for the prediction of the durability of an aggregate. A material with water absorption higher than 6% most likely does not comply with the standards suggested for road pavements material. Although the typical durability tests shows the slight weaknesses of the aggregates deriving from C&D materials compared to the natural aggregates, the tests performed on samples subjected to repeated cycles of wet-dry conditions demonstrate that a long term decay of the strength characteristics is not expected for this material.

The applicability of this material is also confirmed by the consolidated drained triaxial test. The shear strength (Mohr Coulomb's) parameters for the blend were investigated in this study at 100% of the modified AASTHO compaction. The internal angle of friction and cohesion were found to be 51° and 48 kPa respectively. Thus, it is established that the material has sufficient strength to be used as base and sub base layers for the construction of roads.

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Reference

[1] AASHTO (1982) Standard Specifications for Transportation Materials and Methods of Sampling and Testing, Part I and Part II. American Associations of State Highway and Transportation Officials Washington, D.C.

[2] Alexander M. and Mindess S. (2005) Aggregates in Concrete. Spon Press: London, UK

[3] American Society for Testing Material (2011) Method for Consolidated Drained Triaxial Compression Test for Soils,

[4] Angulo S.C., John V.M., Kahn H., Ulsen C. (2003) Characterisation and recyclability of construction and demolition waste in Brazil. In proceeding of Fifth international conference on the environmental and technical implications with alternative materials, San Sebastian, Spain. pp. 209-218.

[5] Angulo S.C., Mueller A. (2009) Determination of construction and demolition recycled aggregates composition, in considering their heterogeneity. Materials and Structures 42:739–748

[6] Araya A.A. (2011) Characterization of Unbound Granular Materials for Pavements. Road and Railway Engineering Section, Faculty of Civil Engineering and Geosciences, Delft University of Technology

[7] Arundeb G., Saroj M. , Somnath G (2011) Direct compressive strength and Elastic modulus of recycled aggregate concrete INTERNATIONAL JOURNAL OF CIVIL AND STRUCTURAL ENGINEERING Volume 2, No 1, 2011

[8] Barbudo A., Agrela F., Ayuso J, Jiménez J.R., Poon C.S. (2012) Statistical analysis of recycled aggregates derived from different sources for sub-base applications. Construction and Building Materials 28 (1): 129-138

[9] Casagrande A. (1948) Classification and Identification of Soils. Transactions of American Society of Civil Engineering 113: 901–930

[10] Committee of Land Transport Officials (COLTO) (1998) Standard specifications for road and bridge works. Pretoria: the South African Institution for Civil Engineering (SAICE)

[11] Committee of State Road Authorities. 1985. Technical Recommendations for Highways – Guidelines for road construction materials TRH14. Pretoria: Department of Transport.

[12] Commonwealth of Pennsylvania Department of Transportation- Materials and Testing Division (2003) Wet-Dry durability test (PA Test Method No. 519)

[13] Council Decision 2003/33/EC establishing criteria and procedures for the acceptance of waste at landfills pursuant to Article 16 of and Annex II to Directive 1999/31/EC

[14] European Normative (2004) Leaching – Compliance test for leaching of granular waste materials and sludge, Part 2: one stage batch test at a liquid solid ratio of 10 l/kg for materials with particle size below 4 mm (without or with size reduction)

[15] Gopala Raju SSSV, Durga Rani K., Chowdary V., Balaji KVGD. (2010) Utilization of building waste in road construction. Indian Journal of Science and Technology 3 (8): 894-896

[16] Hendriks F. and Jassen G.M.T. (2001) Reuse of construction and demolition waste in the Netherlands for road constructions. HERON 46: 109-117

[17] Hobbs G. and Hurley J. (2001) Deconstruction and the reuse of construction materials. Proceedings of the CIB Task Group 39 – Deconstruction Meeting, CIB World Building Congress (Abdol R. Chini (eds) University of Florida), Wellington, New Zealand.

[18] Huang W.L., Lin D.H., Chang B., Lin K.S. (2002) Recycling of construction and demolition waste via a mechanical sorting process. Resources, Conservation and Recycling 37 (1): 22-37

[19] Kourmpanis B., Papadopoulos A, Moustakas K., Stylianou M., Haralambous KL, Loizidou M. (2008) Preliminary study for the management of construction and demolition waste. Waste Management & Research 26: 267–275

[20] Leite F.C., Motta R.S., Vasconcelos K.L., Bernucci L. (2011) Laboratory evaluation of recycled construction and demolition waste for pavements. Construction and Building Materials 25 (6): 2972-2979

[21] Nierker van A.A. and Sheers van J, (2000) The effect of compaction on the mechanical behaviour of mix granulate base course material and on pavement performance. Heron, Vol. 45, No. 3

[22] Poon C.S., Yu A.T.W., Ng LH. (2001). On-site sorting of construction and demolition waste in Hong Kong. Resources, Conservation and Recycling 32 (2): 157–172

[23] Reeves G.M., Sims I., Cripps J.C., Clay Materials Used in Construction (eds) (2006) Geological Society, Engineering Geology Special Publication, London, UK.

[24] Rombi J., Coni M., Portas S. (2012) Experimental investigation on the use of C&DW materials as aggregates for road sub-base. PEAT Journal 13: 49-58

[25] Roussat N., Mehu J., Abdelghafour M, Brula P., (2008) Leaching test behaviour of hazardous demolition waste. Waste Management 28 (11): 2032-2040

[26] Sampson L.R. and Roux P.L., (1985) The durability mill test for the assessment of unstabilized aggregates. National Institute for Transport and Road Research.

[27] Solyman Mahamoud (2005) Classification of recycled sand and their application as aggregates for concrete and bituminous mixture. Kassel University Press, Kassel

[28] South African Bureau of Standards (SABS) (1976) Abrasion resistance for coarse aggregates (Los Angeles Machine method)

[29] South African Council for Scientific and Industrial Research, Committee for State Road Authorities, Highway Materials Committee, Materials Testing Subcommittee, National Institute for Transport and Road Research (1986) Technical Methods for Highways TMH1- Standard Methods of Testing Road Construction Material. National Institute for Transport and Road Research. Pretoria, South Africa.

[30] South African National Standard (SANS) (2011) Part AG21: Determination of the bulk density, apparent density and water absorption of aggregate particles passing the 5 mm sieve for road construction materials.

[31] Theyse H.L. (2002) Stiffness, Strength, and Performance of Unbound Aggregate Material: Application of South African HVS and Laboratory Results to California Flexible Pavements. CSIR Transportek , Pretoria, South Africa.

[32] Theyse, H L and Muthen, (2000) M., Pavement analysis and design software (PADS) based on the South African mechanistic-empirical design method. CSIR Transportek , Pretoria, South Africa

[33] Wahlström M, Laine-Ylijoki J., Määttänen A., Luotojärvi T., Kivekäs (2000) Environmental quality assurance system for use of crushed mineral demolition waste in road constructions. Waste Management 20 (2-3): 225–232

[34] Wu, Y., Parker, F., Kandhal, K. (1998) Aggregate Toughness/Abrasion Resistance and Durability/Soundness Tests Related to Asphalt Concrete Performance in Pavements. National Center for Asphalt Technology of Auburn University

Chapter 5

5 Monitoring and analysis of an instrumented road embankment built with C&D materials

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Abstract

In civil industry the use of alternative materials such as construction and demolition (C&D) waste is considered advantageous for engineering but also for environmental reasons. Several laboratory studies have shown their qualities that make them suitable for civil engineering purposes and ensure the replacement of natural aggregates in different applications. However, these analyses are not sufficient for fully assessing the behaviour of C&D materials under real working conditions.

The aim of the research is to verify the real applicability of C&D materials and whether C&D wastes and natural soils represented by the same classification index have similar behaviour in field. In this paper the in situ monitoring of an experimental road embankment made by a waste material coming from the deconstruction of a disused military area in the

Durban Municipality is reported. Deformations and variation of Stresses, Moisture Content and Densities inside the earthwork were constantly recorded at the passages of trucks of known characteristics over a period of 1 year. The observation of the material response to dynamic loads and environmental actions allowed the determination of the Young's modulus and the extrapolation of possible long term behaviours. The veracity of the Elastic parameters determined in field by means of embedded instruments has been checked by comparing to those obtained in laboratory and by FWD back-analysis.

Key words: monitoring, recycling, C&D waste, FWD, LVDT, TDR, pressure cells, elastic modulus, vehicle-pavement interaction

5.1 Introduction

Worldwide civil industry has been incentivized by governments on the use of recycled materials for reducing consumption of primary aggregates (Richardson, 2013). One of the main components of waste is the construction and demolition (C&D) material, which, due to its nature, is suitable for being reused in various civil engineering applications (Poon et al, 2001). Currently C&D wastes are currently applied as replacement for virgin aggregates in "rural or low traffic" roads (Jiménez, 2013). The applicability of these materials is proved by numerous studies which verify the equivalence of their geotechnical properties with those of natural aggregates by means of standard laboratory tests (Martìn-Morales et al, 2013). Although the high number of these studies is determining their inherent characteristics, the behaviour in real working condition is still fully not yet understood (Jiménez, 2013). This is mainly due to the susceptibility of the C&D waste to the characteristics of the originating structures that makes difficult to predict its composition and generates a high heterogeneity (Angulo and Muller, 2009). Major limitations of laboratory analyses for testing granular aggregates is, in fact, that they examine only limited quantities, sometimes specific grading, of the total material and, trying to replicate the real stress field developed in field by means of only simple approximations, they cannot fully anticipate their real behaviour (Vorster and Gräbe, 2013). For this reason some authors are moving their attentions to approaches that investigate the short and long term behaviours of this alternative aggregates by the observation of full scale test beds (Rombi et al, 2012).

Monitoring alternative construction material in real working conditions allows determining the necessary geotechnical characteristics for engineering purposes. Moreover these observations help to understand in situ behaviour under different weather conditions and in different geographic areas (Al Qadi et al., 2010). It is also essential to have the certainty that an alternative material is equivalent in terms of durability, as this could compromise the stability and serviceability of a road. The uncertainty in the determination of these characteristics has in fact discouraged the use of alternative resources in place of natural ones.

The realizations of small sections built with new materials and constantly monitored help to understand better their behaviours and to observe abnormalities to estimate the useful life before using in large scale (Della Rizza, 2010). Monitoring of a road section has three main goals, the assessment of the surface, structure conditions or the identification of environmental issues (Stryk and Pospil, 2009). However the most used methods are those that evaluate the structure conditions during its construction, before opening the road to the public and during its service.

Monitoring approaches are divided into two main categories. The first group embraces the classic methods, which provide information by means of laboratory tests on samples extracted from the structure or by means of non-reproducible in situ test. These approaches are commonly called “destructive” because they are cause of damage to the structure. The second category, named as Non Destructive Testing (NDT) methods, includes those approaches that evaluate the condition of a construction indirectly. Those techniques interpret how waves, such as electromagnetic or vibrations, propagate from the surface through the subgrade (Cartz, 1995 and Hellier 2003). Change of densities, elevation of the water table of other physical characteristics can be determined by this approach. Typical of road engineer is the interpretation of the deflection curve caused by the Falling Weight Deflectometer (FWD) for determining elastic moduli of the pavement layers (Marradi and Marvogli, 2007), the use of Nuclear Densometers for the evaluation of the Relative compaction degree or the real time investigation of road and railways structure by means of GPR installed in within vehicles (Daniels, 2004).

Other approaches are based on the analysis of results coming from sensors embedded into the road layers. They usually measure deformations and pressures but other parameters such as moisture content and temperature are observed. These methods register the behaviour of an engineering material subjected to real dynamic loads of different nature, intensity and velocity (Al Qadi et al., 2004). The magnitude of these readings can be related to many factors such as compaction level, grading and materials nature (Coni et al, 2012). The use of nano-sensor may increase the accuracy of the measurements providing more realistic results, which could give more correct assessment of materials used and for improving the management of road maintenance (Steyn, 2011).

In this paper, the assessment of the applicability of typical C&D material in road construction by the analysis of an instrumented embankment entirely built with the same is investigated. Only one type of material was used in the entire embankment for studying better since it is not influenced by other aggregates in other layers. In this way it is possible to define the behaviours and determine on which layer it can be used. From the previous analysis it seems that the utilization can be in the structural layer as the G4 as well as selected layer.

The material under analysis was a combination of crushed concrete and masonry and came from the deconstruction of the residential buildings of an ex-military area in Durban, South Africa. The properties of the aggregates used were extensively investigated and compared to natural aggregates for unbound base and sub-base layers according to national specifications. The behaviour of the test bed was monitored over a period of 12 months by means of in situ tests and instrumentations. These sensors were embedded at different depth in order to assess the stability of the structure, monitor displacements and pressures at the passage of loaded trucks, changes of moisture content inside the road structure. Results from in situ tests allow affirming a similar behaviour of C&D material compare to natural soils and an increasing of elastic modulus of the embankment.

5.2 Materials and Methods

5.2.1 Characteristics of subgrade and the construction of the embankment

5.2.1.1 Properties of materials

The embankment was built on a dark brown weathered tillite subgrade. Due to the high plasticity and low bearing capacity a 300 mm thick layer of crushed concrete was spread on it to improve bearing and reduce settlements. The properties of the crushed concrete, coming from the same deconstruction, were determined in laboratory and are summarised in Table 5-1.

Table 5-1 Properties of crushed concrete

Crushed concrete	
SA classification	G3
AASTHO class.	A1-a (0)
USCS	GW
Plasticity	NP
Water absorption	5.5%
OMC	12.0%
MDD	19.18 kN/m^3
CBR	114.52%
LAA	36.46%
ACV	29.36%
DMI	mill <35% as request
Flakiness index	10%

The material used for the construction of the embankment consists of 75% of masonry and 25% of crushed concrete by volume in order to reproduce the ratio of these in standard South African residential buildings. The materials were crushed in order to have the specific particle size distribution required by the national specifications for base or sub-base layers.

Table 5-2 shows the properties of the manufactured blend indicating the results of the main laboratory tests for road aggregates.

Table 5-2 Properties of manufactured blend

Manufactured blend	
SA classification	G4
AASTHO class.	A1-a (0)
USCS	GW
Plasticity	NP
Water absorption	6.9 %
OMC	13.2%
MDD	18.72 kN/m^3
CBR	98.77%
LAA	43.90%
ACV	35%
DMI	mill <35% as request
Flakiness index	12%

Although very good classification outcomes for both the materials were achieved, the results of the LA and ACV tests expect durability issues. The values obtained of ACV and LAA have shown a clear relation with the water absorption, which is commonly very high for C&D wastes. High water absorption also influences the quantity of water necessary for an optimal compaction.

CD Triaxial Tests on samples of blends saturated at the optimum moister content were carried out. Results of these tests demonstrate high strength achieving an internal angle of friction of 51° and cohesion of 49 kPa. The elastic modulus increases from 24 to 48 MPa for increasing confining pressures σ'_3, which ranges from 30 to 80 kPa, as summarised in Table 5-3.

Table 5-3 Triaxial test results

Cohesion [kPa]	48.96		
Angle of internal friction	51.34°		
σ'_3 [kPa]	30	50	80
σ'_d [kPa]	479	652	973
E' [MPa]	23.97	32.43	48.35

According to Theyse's (2008) experience manufactured blend material has cohesion and internal angle of friction equivalent to G3 material of South African classification. This material has excellent geotechnical characteristic for using as a base. Moreover it is generally found in road with high volume of traffic.

5.2.1.2 Embankment geometry

The experimental embankment was built on the open side of an existing road; it is 50 m long, 1.80m high and 4 m wide on top. Due to the morphology of the site, the embankment shows a constant slope of 7%. Base and Sub-base of the structure were composed of the C&D blend to limit the number of unknowns in the study for back analysis. The embankment was built by successive layers of 300 mm and no seal was provided on top. A typical section is shown in Figure 5-1.

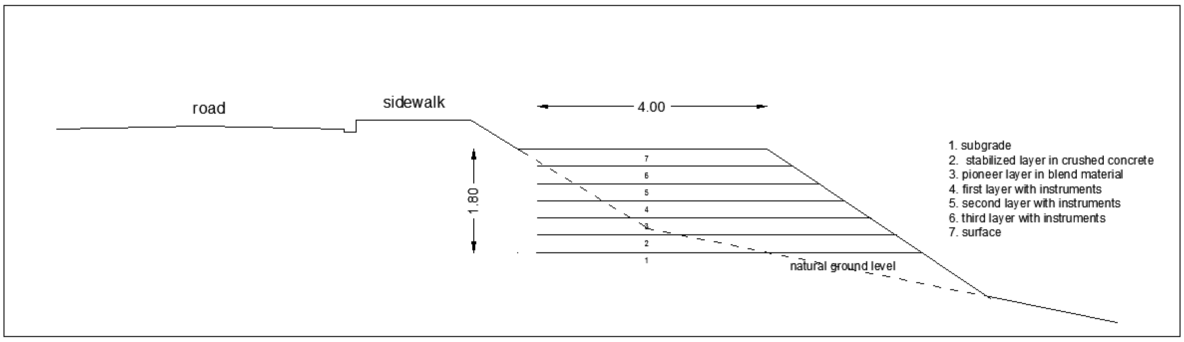

Figure 5-1 Typical section

The natural subgrade, which was slowly compacted for reducing future settlements, is identified with the number 1. The subgrade was overlaid by 300 mm of crushed concrete (layer #2) compacted to 93% Mod AASHTO for further stabilization. The compactive requirement for five layers above this were of the approved manufactured blend material was 95% mod AASHTO minimum.

Three groups of sensors, installed inside the structure, each of them was positioned at the interface of the four layers of compaction from the top of the road (300 mm, 600 mm or 900 mm from the surface). Each set of sensors included one earth pressure cell, one TDR, one LVDT in transversal direction and two LVDTs positioned in vertical direction, one according to the force of gravity and the other according to the slope. The position of the instruments is shown in Figure 5-2.

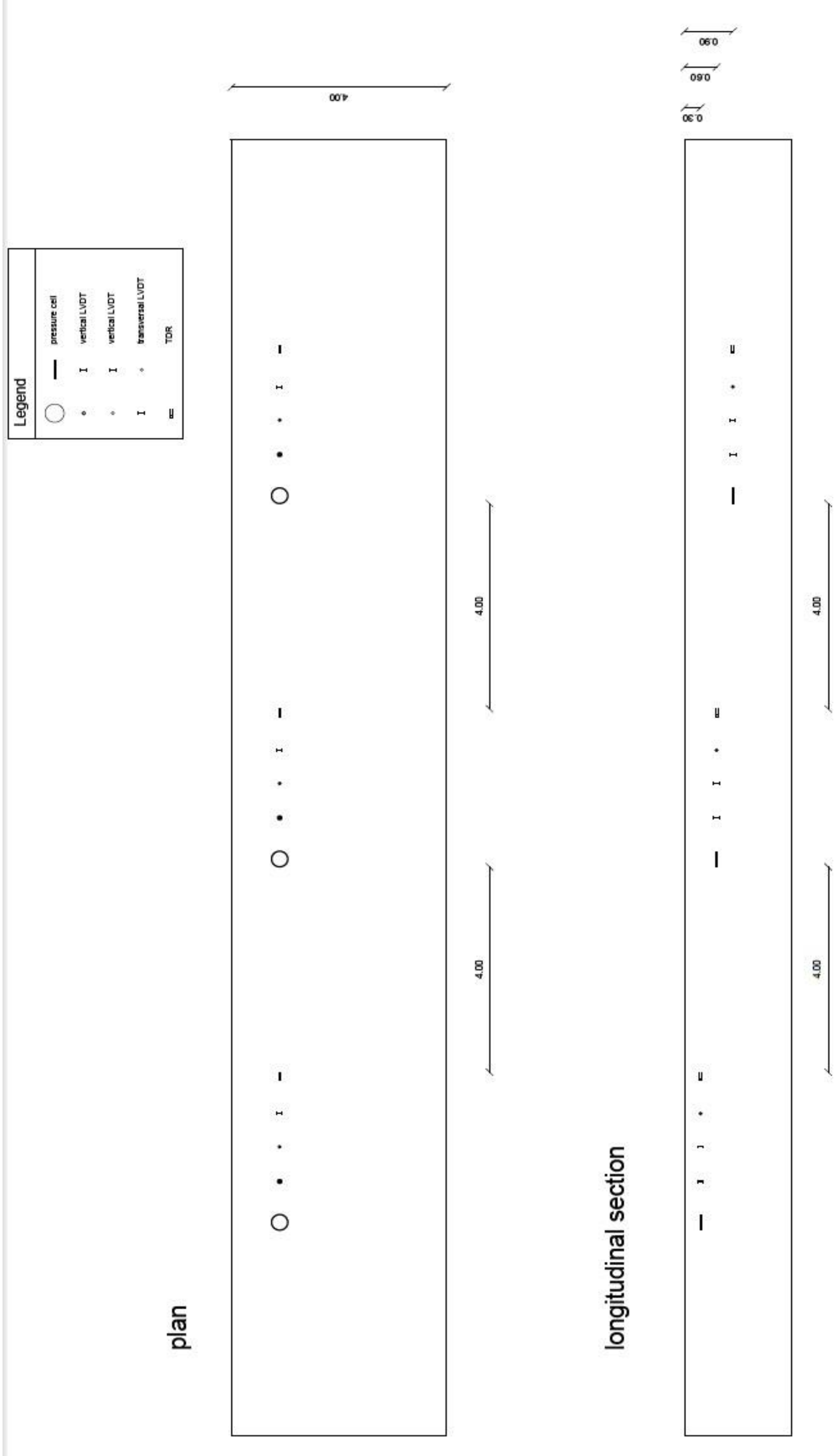

Figure 5-2 Position of instrument in the embankment

After the placement of monitoring instrumentation, rolling was carefully controlled to prevent damage to the sensors. The compaction procedure after placement of instruments was 4 passes of the roller without vibration and then light vibration for a minimum of 12 passes.

The construction of the embankment started on the 20th of February 2012 and was finished in 5 weekdays. The embankment was monitoring for a period of 10 months to study the long term behaviour of the C&D waste under heavy duty traffic loads.

5.2.1.3 Embedded sensors

The groups of sensors were embedded to describe the material behaviour and extrapolate the information necessary for future applications of the same type of C&D material.

The Linear Variable Differential Transformers (LVDTs) manufactured by HBM were used to verify displacements during the transit of trucks. In order to enable the transfer of the deformations induced from the material to the sensor the probes the probes were modified installing two plates at the distance of 150 mm, one fixed to the instrument and one at the top, free to move with the LVDT spring as shown in Figure 5-3. A bellow was placed between the two plates to protect the instrument. The approached followed was the same used by Prof Al Qadi (2010) in his studies on pavement behaviours.

Figure 5-3 Modified LVDT

The maximum measurable displacement is 50 mm, to take into account the displacements due to the compaction of the upper levels and to allow the measurement of deformations of both compressive that traction.

The three Earth Pressure Cells used for measuring the variations of vertical stresses were supplied by the Canadian RST Instruments Ltd. The diameter of the cells installed is 300 mm and the capacity is 50 psi.

Time Domain Reflectometers (TDRs) were installed to check the moisture content. These devices are often used in agriculture for irrigation scheduling or along the telecommunication lines for revealing growing resistance levels on parts which can be corroded, but also for research in other disciplines. In geotechnical field they are commonly used for slope stability studies (Dowding and O'Connor, 2000).

The Model CS616 probes manufactured by Campbell Scientific consist of two stainless steel rods, 300 mm long, which are the two opposite polarities. The moisture in the soil allows the passage of electric current, the frequency f expressed in Hz is a function of the soil crossed and inversely proportional to its magnitude. Due to the different nature of the material a specific calibration was needed. The Figure 5-4 shows the calibration curve, function of the moisture content w, obtained in the laboratory.

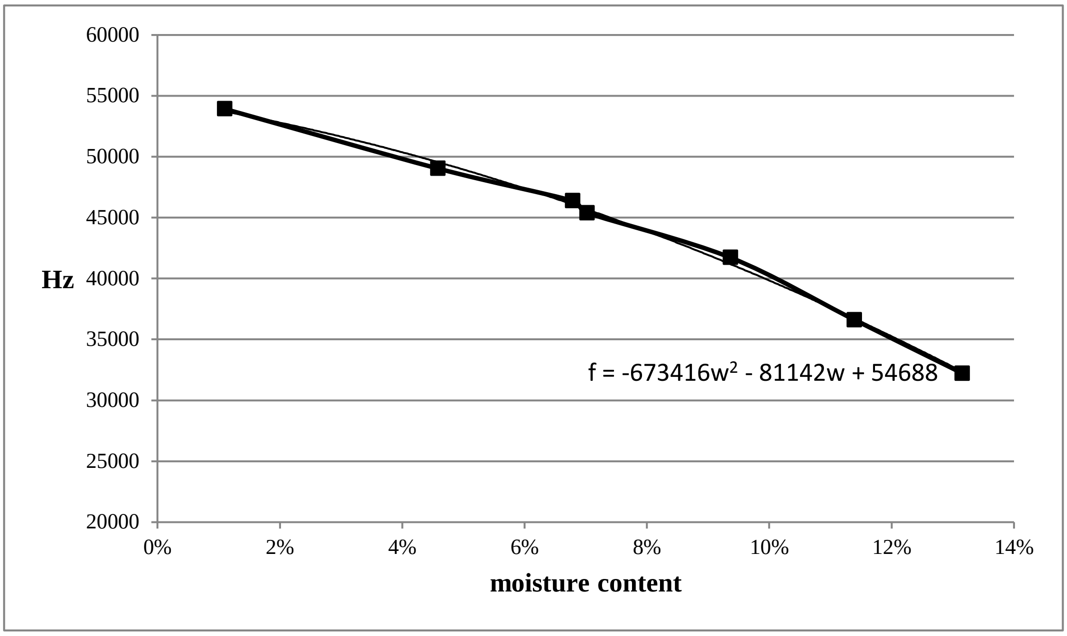

Figure 5-4 Curve for the calibration of TDRs

The Data Acquisition System produced by IOtech was an assembly of different modules in order to connect the cables of each instruments embedded. The main modulus was the Daqbook2000 which produces text files of the results, two dbk65 for LVDTs and pressure cells and one dbk10 for TDRs.

5.2.2 In situ tests on the embankment

In situ tests were carried out in order to monitor the material for short and long terms. Deflections, displacements, moisture contents were also investigated for a year.

5.2.2.1 Falling Weight Deflectometer (FWD) test

Based on the recorded deflection registered at the impact of a standardized mass falling on the road surface, the FWD test allows determining elastic characteristics of the layers underneath (Das, 2010). This approach was developed in France in the 60s and it is one of the most used in-situ tests today in road engineering.

The elastic properties of the embankment were studied by means of FWD tests at the completion of the road and 7 months later to verify variations and alterations in the functionality. The measurements were taken at the same chainages, three were at the centreline, three at the internal side and the same amount at the slope side.

5.2.2.2 Dry density

Dry density and moisture content of the embankment were assessed by nuclear gauge, which is commonly used in road construction for its practice and simplicity. It works by source of gamma radiations and a receiver which measures the amount of radiation that passes through the soil in between. For these measurements, a Troxler 3440 was used.

Ten fixed spots for density tests were chosen along the centreline of the embankment. Measurements were taken weekly over a period of 6 months.

5.2.2.3 Heavy traffic load tests

The measurement of the effects due to the applications of external stresses in correspondence to the sensors embedded road section were carried out two times per month. The readings were firstly performed in absence of any external load, to observe possible modifications in in the material with time, and in conjunction with the passage of a fully loaded truck. Particular attention has been put in the truck for having the same characteristic when the test was carried out. The load was kept constant to notice the effect of the load in the embankment by means of the displacements during the time.

In detail, a Man Evolution D20 was used. Three axles, single in front and rear double wheels, constant tires pressure equal to 800 kPa and an average weight of about 240 kN. The distribution of the truck weight on the axles was also determined: 29 % was on the front axle, 36% and 35% on the second and third.

The tests were performed with stationary vehicle on the sensors and at three different speeds, 5, 10 and 15 km/h, for assessing the response of the material when load was applied. The side wheels of the truck have been passed exactly over where sensors have been installed.

The collection of the data was registered and verified real time by a computer connected with a Data Acquisition System.

5.3 Results and discussions

5.3.1 Results from Falling Weight Deflectometer (FWD)

At the fall of a standardised mass, the FWD device measures the vertical displacements in radial direction at fixed distances from the point of impact. In association with the Boussinesq's theory, it allows to study the Elastic behaviour of a soil. The instrument used was able to record the ground movements up to 1.8m from the centre of the plate.

Nine relevant measurement stations were tested on the 16th April 2012 and, seven months later on 23rd November 2012, the experiment was repeated in the same spots. Figure 5-5, Figure 5-6 and Figure 5-7 show the deformative response at the ground surface represented by the nine deflection bowls registered on the testing days. An overall improvement was observed, the vertical deformation reduced of 60%, due to the natural consolidation of the soil and also to the wheels compaction of the truck load tests performed and some other vehicles when no test were taken in place.

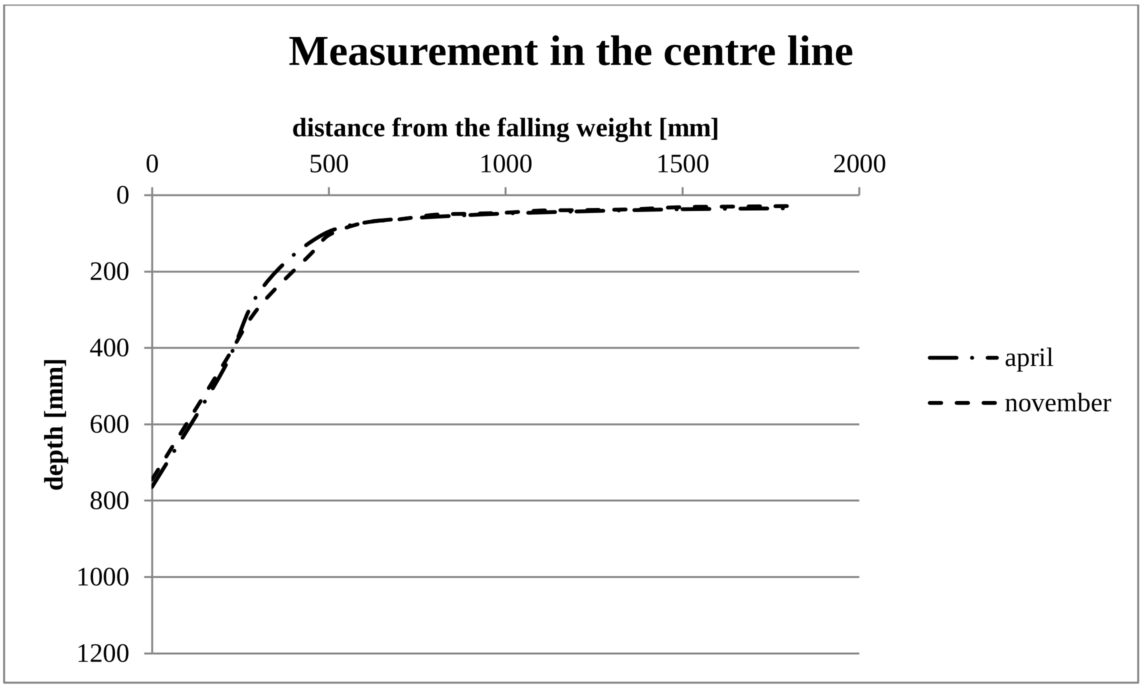

Figure 5-5 Deflection bowls on the centre line

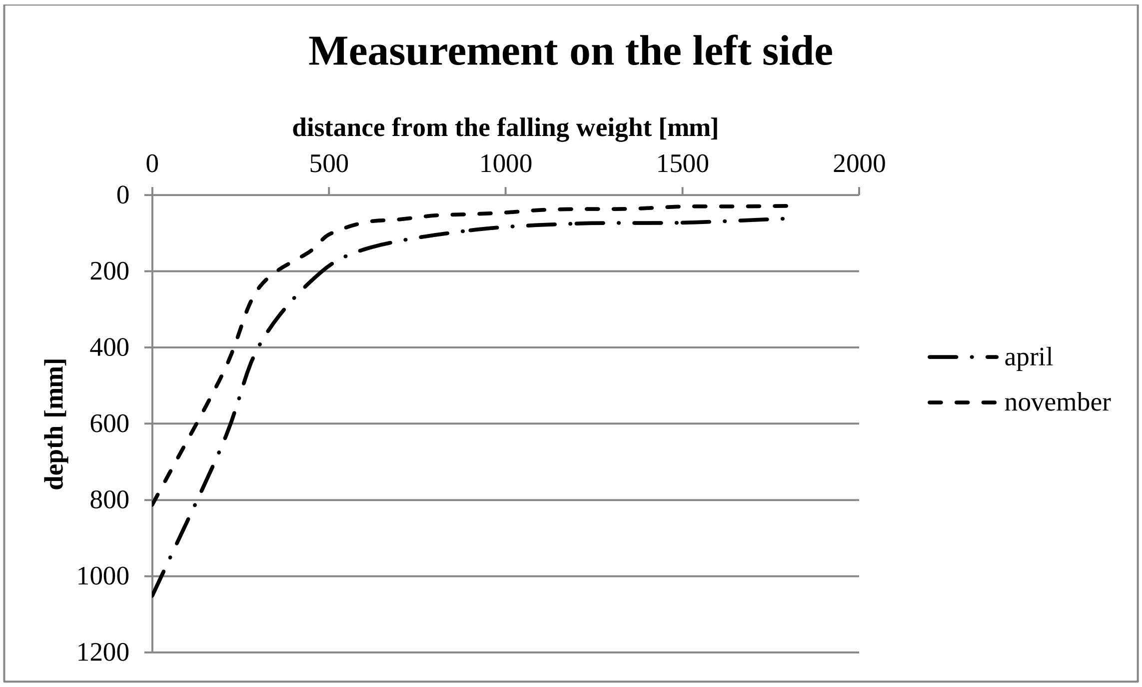

Figure 5-6 Deflection bowls on the left side

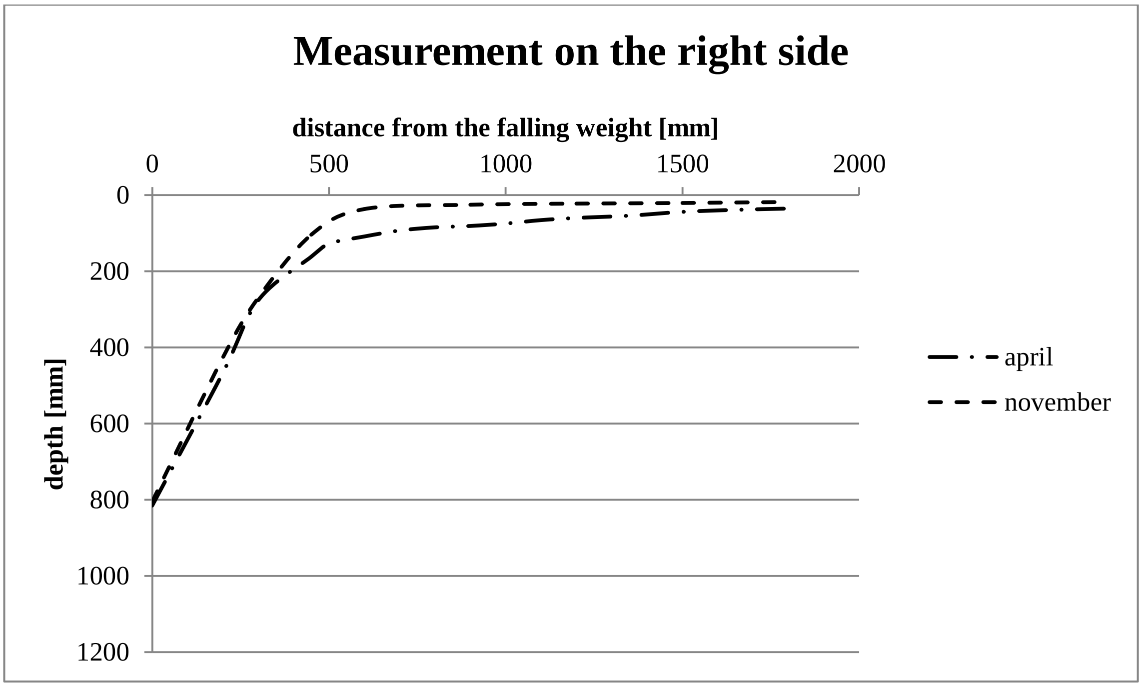

Figure 5-7 Deflection bowls on the right side

The software Rubicon was used to back-calculate the displacement bowls and determine the Young's moduli E. The results of this analysis were also confirmed by means of a FE model in Rocscience Phase2.

Table 5-4 summarizes the values of E determined for each FWD test. It can be observed that all elastic moduli have increased during the testing period, especially on the left, confined, side.

Table 5-4 Elastic moduli in MPa backcalculated by FWD test

section		section1	improvement	section2	improvement	section3	improvement
April 2012	left side (a)	102.41		133.38		127.77	
	centre line (b)	180.2		197.43		205.93	
	right side (c)	164.99		186.54		109.64	
November 2012	left side (a)	220.84	116%	220.44	65%	220.43	73%
	centre line (b)	197.41	10%	243.71	23%	205.06	0%
	right side (c)	267.1	62%	244.87	31%	205.49	87%

5.3.2 Nuclear gauge test results

Starting after the construction of the embankment a periodic record of the dry unit weights verified along the centre line of the test bed was made. Figure 5-8 shows the readings and the trends of 150 and 300 mm depth of the dry density during the six months of observation. For simplicity, only the daily average values measured in the 10 station have been shown. As expected, as natural soils, the dry unit weight has increased considerably in the first 40-50 days. After this period, the relative compaction (R) stabilises at about the 102% of the mod AASHTO in the superficial 150 mm of blend.

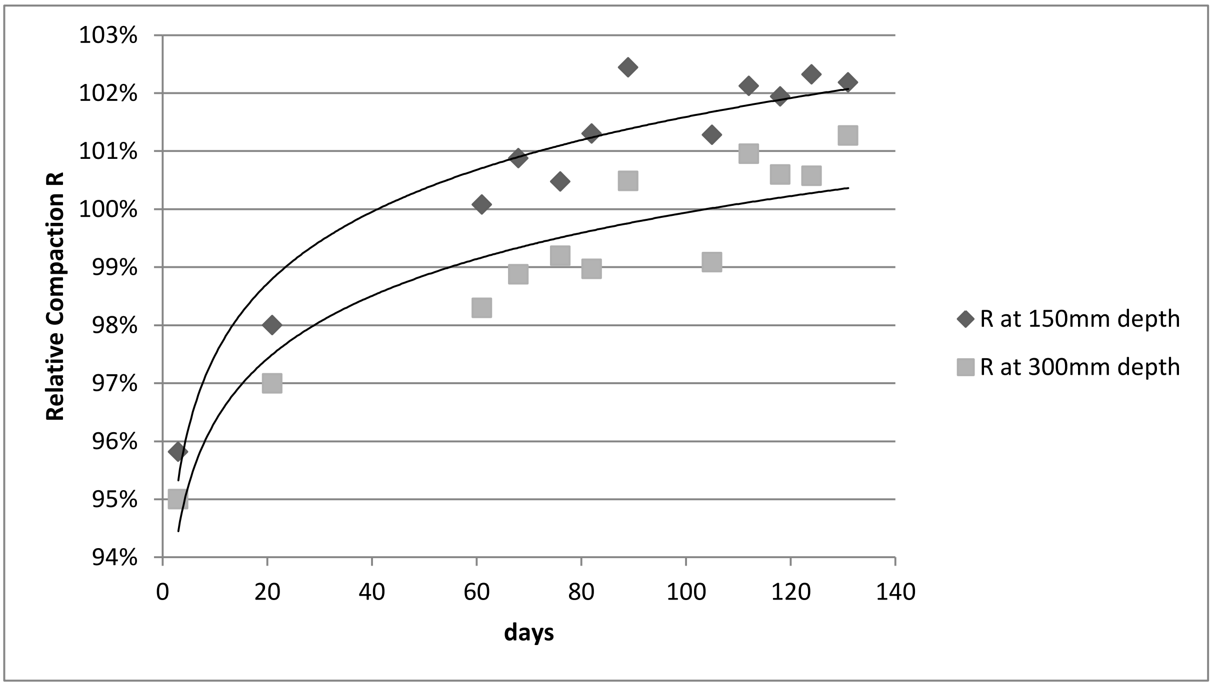

Figure 5-8 Relative compaction registered by means of nuclear gauge

The increment of compaction is in line with the increment of Young’s modulus observed in the FWD tests. As determined by different authors (Obrzud and Truty 2012, Kezdi 1974, Prat et al. 1995), there relative compaction and Elasticity behaviour are directly related.

The capacity of the instrument to simultaneously determine the soil moisture has allowed to observe that dry unit weight the readings made by means of the nuclear gauge are influenced by its variation. Those two parameters have in fact shown clear inverse proportionality.

To complete of information given by the nuclear gauge the trend of the moisture content of the pavement has been taken and shown in Figure 5-9. As notice the surface layer is affected by weather and pavement conditions. Further tests have shown, however, that this does not occur within the embankment.

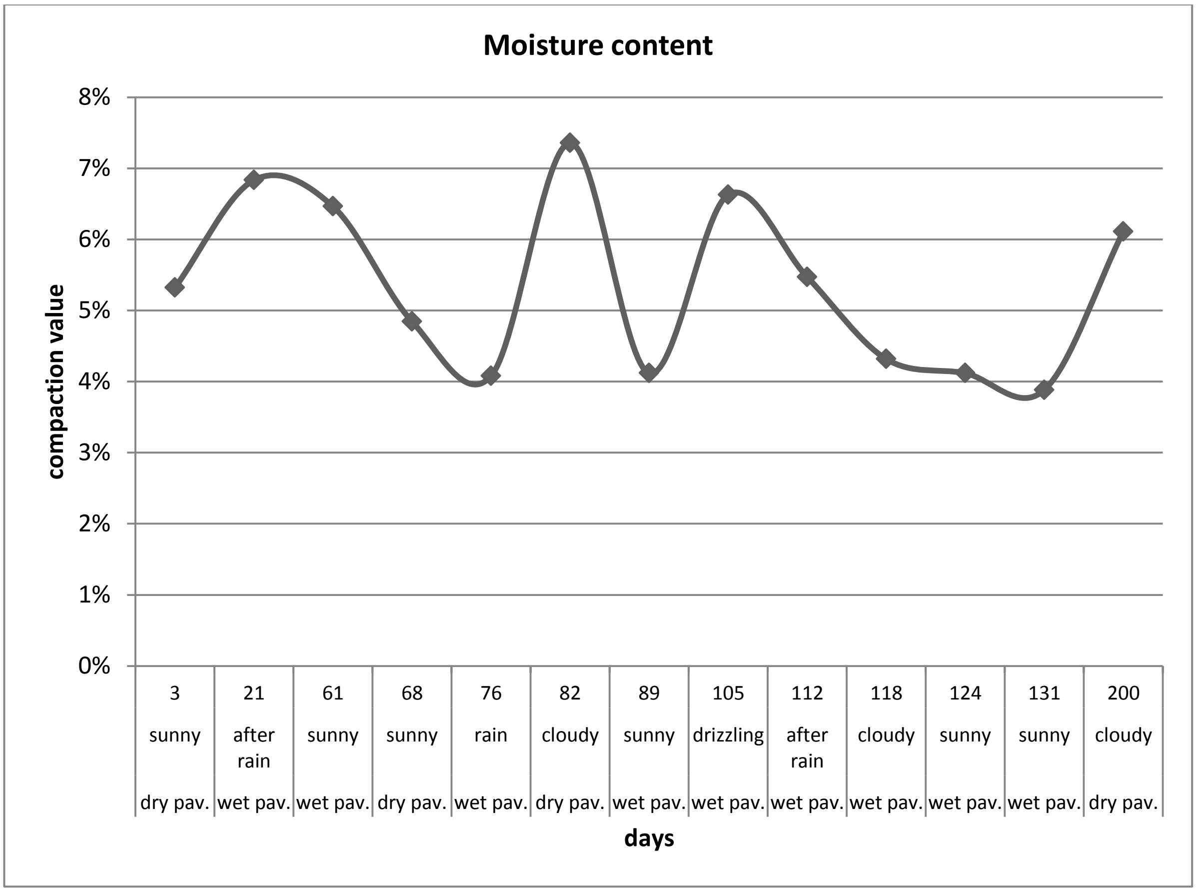

Figure 5-9 Moisture content of the material using Nuclear gauge

Material samples were taken in the same day of these measurements and have been oven dried. The results were congruent.

5.3.3 Results from instruments embedded in the experimental embankment

5.3.3.1 Measurements of the instruments during months without applying any stress

The time trend analysis of the LVDTs displacements in absence of external loading was used to verify compaction increment observed by means of Nuclear Gauge and FWD. The continuous vertical LVDTs registered maximum settlement of 0.3 mm at 300 mm depth and 0.4 mm at 600 mm depth, as shown in Figure 5-10.

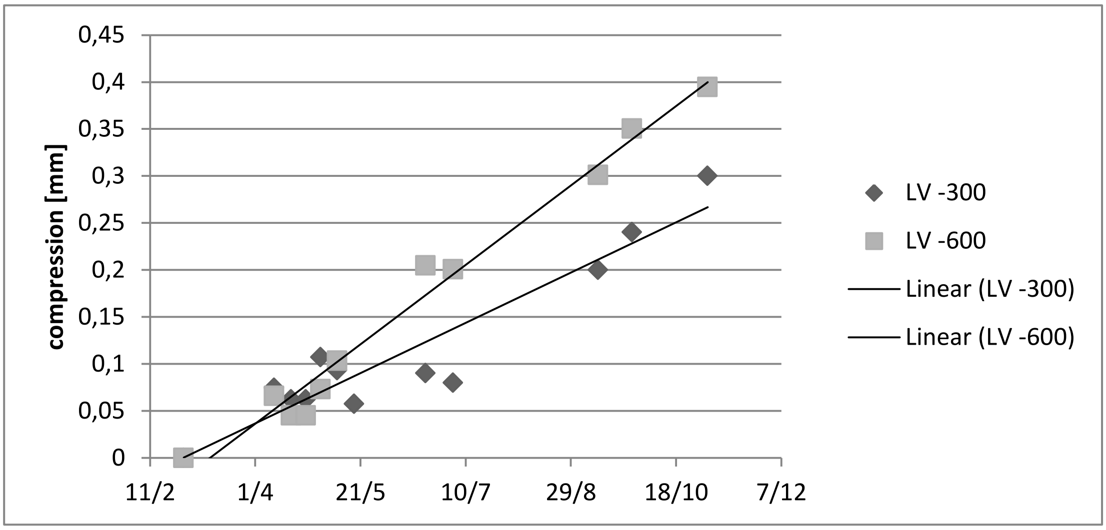

Figure 5-10 Displacements of the vertical LVDTs at 300 mm and 600 mm depth

No different displacements have been noticed in LVDTs installed in the transversal way.

Figure 5-7 represents the trend of the moisture content registered from February to November in three different points and depths of the embankment. The measured values reaches about the equivalent values of the OMC of the material (13.2%) and it slightly changed in case of rain. It was observed some increase up to 15.8% when a lot of rain came, at the end of May and during the raining season (October-December), hence the water could filter through the particles.

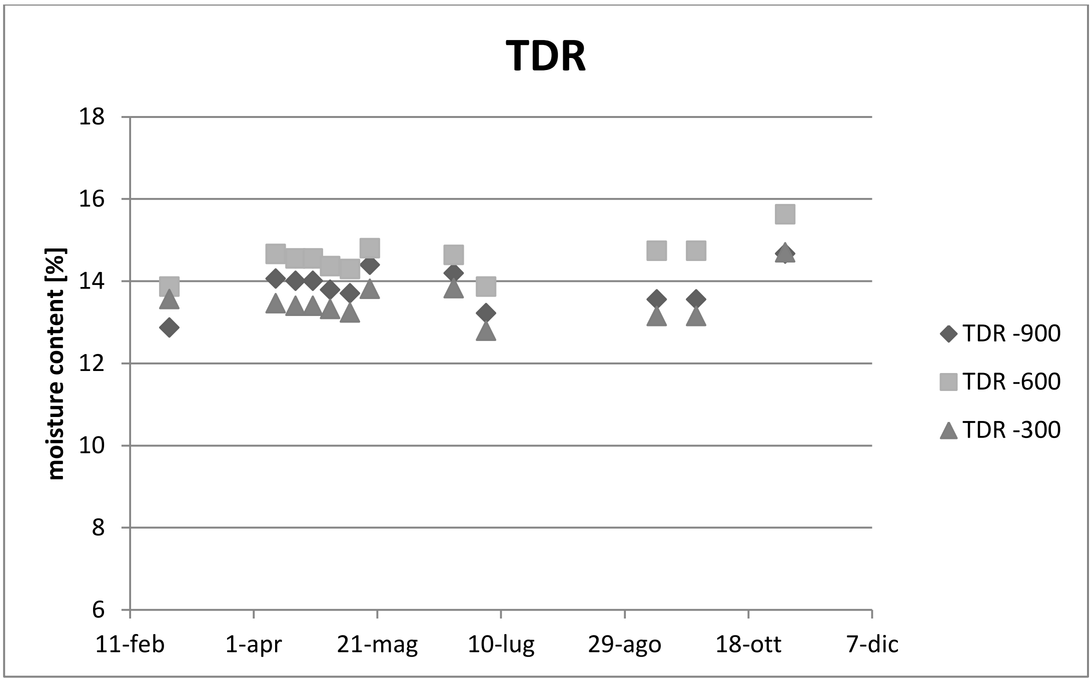

Figure 5-11 Moisture content value during monitoring time taken by TDR at 300 mm, 600 mm and 900 mm depth

5.3.3.2 Stress and displacements at the passage of a heavy loaded trucks

Test with the truck Man D20 common rail evolution TGA 33.360 was performed for assessing the behaviour of the used C&D material when subjected to vehicular loads.

In order to boost the LVDTs and Pressure Cells's readings, the truck was heavily loaded to achieve the total weight of 241.3 kN. The average stress measured by means of pressure cells ranged from 24 kPa at 900mm, 62 kPa at 600mm and 180 kPa at 300mm depth.

Table 5-5 show the displacements according to each speed. Differently from what observed for the stresses increment, the truck speed affected the magnitude of the displacements as reported in Figure 5-8. Higher speeds correspond to smaller displacement and vice versa. . This event has been noticed in other study (Al Qadi et al 2003 and Al Qadi et al 2004).

Table 5-5 maximum displacements registered by vertical LVDTs per each speed

speed km/h	depth [mm] 300mm	600mm	900mm
0	0.75040	0.54230	0.46600
5	0.58471	0.38934	0.32200
10	0.47471	0.28339	0.22000
15	0.42036	0.22439	0.16000

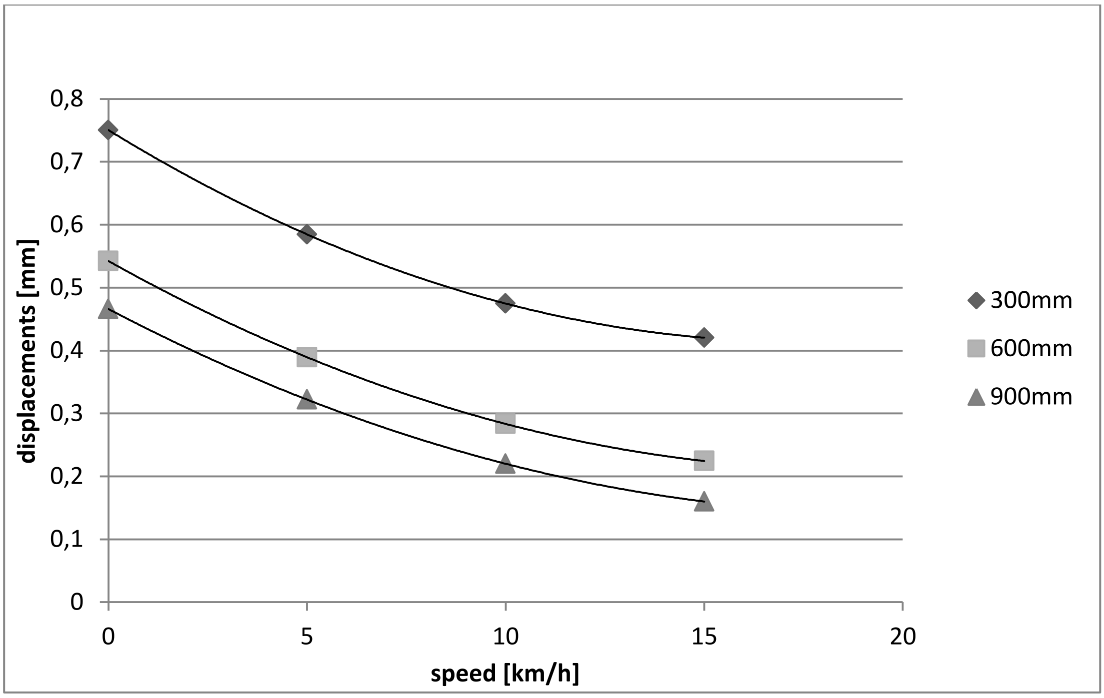

Figure 5-12 maximum displacements registered by vertical LVDTs per each speed

There has been no movement in the LVDT positioned transversely in the embankment during the passage of trucks. the deformations are much lower than what the instrument can measure. This is due both to a good compaction but also to the good properties of the material.

5.3.3.3 Back-calculation of dynamic elastic modulus by means of Mechanical-empirical Pavement Analysis & Design Software (mePads)

The Mechanical-Empirical Pavement Analysis & Design Software (mePads) software is used for back-calculating the elastic modulus of the blend material used for the embankment. This software is based on the South African Mechanistic Pavement Design Method developed by CSIR Transportek. The software combines a linear elastic stress-strain computational engine with pavement materials models classified according to South African Classification.

The structure of the embankment was set as it was built with soil, 300 mm of concrete layer and 1200 mm of compacted blend material as represented in Figure 5-1. For the load definition plan the two rear axles were considered with a wheelbase of 1400 mm having double wheels at the distance of 200 mm. The load of each wheel of the second axles of the truck was 21.6 kN and the each wheel of the last axles was 21 kN according to the distribution of the load previously mentioned. Figure 5-13 represents the load position in a graph.

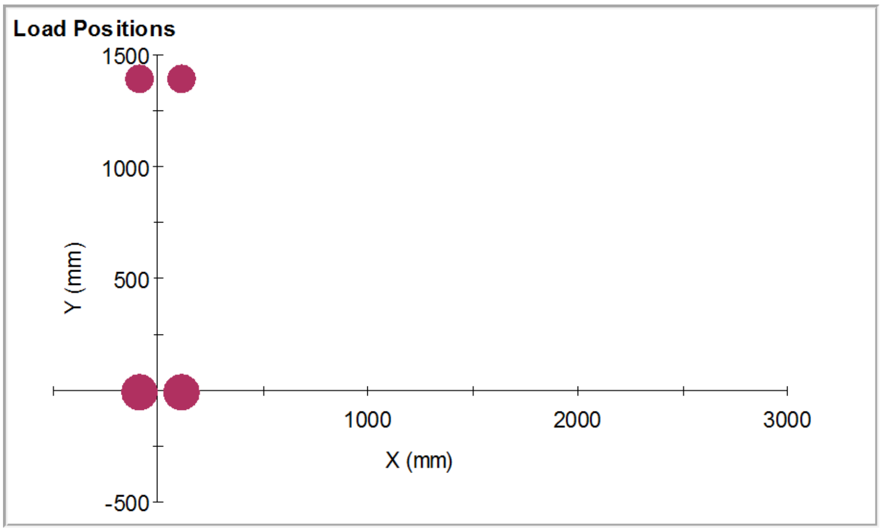

Figure 5-13 Wheels positions of the truck

The values of the displacements and stresses obtained respectively from the LVDTs and from cells of pressure during the passage of the truck at a speed of 0, 5, 10 and 15 km/h (Al Qadi et al, 2010) were used for the backcalculation.

From previous studies of soil in the surrounding area, the subgrade was found having a Young modulus of 40 MPa, which is used in the software. Crushed concrete and blend material, respectively classified as G4 and G3, maintained proportionality in the elastic modulus of 2.22%, as studied by Theyese and Muthen (2000).

Once found the elastic moduli of the materials to 0 km/h they were increased by the same percentage to find the moduli during the passage of the truck. Table 5-6 shows the elastic moduli found by means of the software.

Table 5-6 Elastic modulus for each material depending on truch's speed

E	0 km/h	5 km/h	10 km/h	15 km/h
blend	129.00	179.31	254.62	313.18
concrete	131.87	183.29	260.28	320.14
subgrade	40.00	55.60	78.95	97.11

It is observed that Young's modulus of blend grows linearly with the increase of the speed of the truck as shown in Figure 5-14.

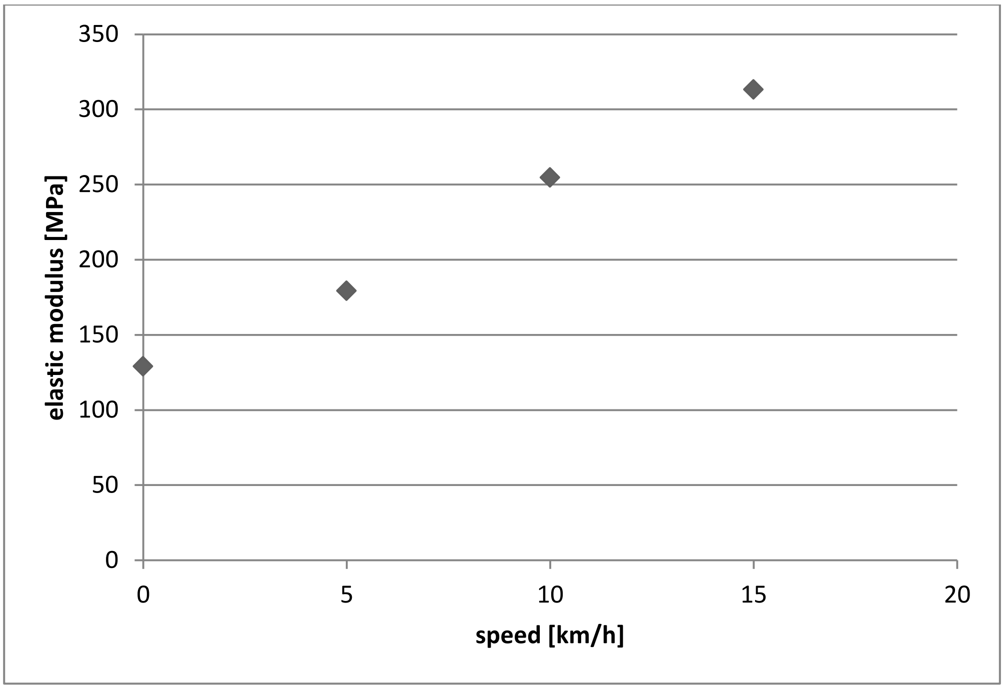

Figure 5-14 Elastic modulus versus velocity for blend material

5.4 Conclusions

The analyses on an experimental road embankment made by C&D waste material demonstrate the applicability of this material in so far. Its behaviour is like a natural granular soil while having different characteristics.

The monitoring on this test-bed was performed in two different ways, one with in situ test and the other by sensors embedded inside the embankment.

The in situ test provide the use of the FWD test, repeated two times for assessing the changing in the deflection bowls and in the improving of elastic moduli, which are higher due to consolidation and the truck passages. The monitoring done by means of embedded sensors lead to conclude that the displacements are function of the speed, they are smaller when the truck speed increase and the moisture of the embankment increase only when there are heavy rains, otherwise it seems to keep the original moisture content.

The methods for calculating the elastic modulus are different and the comparison to each other's is difficult because the final value depends on the boundary conditions, the grade of compaction and the applied pressure and the formula used. Three techniques were taken into account for C&D material under exam: the triaxial test in laboratory, the FWD test on the surface and by means of backcalculation South African software mePads using data from embedded sensors. This material has the lowest value of elastic modulus in the laboratory test than those calculated by means of FWD. The elastic modulus found through backcalculation with mePads software change according to the speed of the truck and it rises linearly when the speed increases as well. The more representative method for calculating the elastic moduli is the one using the embedded sensors since the embankment is monitored entirely. Anyhow this approach can be improved but always compare with the standard method commonly used.

In conclusion the results obtained lead to observe G4 characteristics in this C&D material which can be used as a base in road pavements category C and D.

Acknowledgment

Authors would like to acknowledge Mr Krishna Naidoo, from eThekwini Municipality, for the finding the experiment venue and allowing its use, Mr Kevan Rocher exco member at Raubex PTY LTD for his effort in the embankment construction, the students who helped in the instrumentation process and Prof Chandra for sharing with me his experience and editing this paper.

Reference

[1] Al-Qadi I. L., Loulizi A., Lahouar S., Flintsch G. W., Freeman T. E. (2003) Quantitative Field Evaluation and Effectiveness of Fine Mix under HMA Base in Flexible Pavements, Transportation Research Board, 82nd Annual Meeting, January 12-16, 2003, Washington, D.C.

[2] Al Qadi I, Loulizi A, Elseifi M, Lahouar S, The Virginia Smart Road (2004) The Impact of Pavement Instrumentation on Understanding Pavement Performance

[3] Al Qadi I, Portas S, Coni M, Lahouar S, (2010) Runway Instrumentation and Response Measurements, Transportation Research Board

[4] Angulo S.C., Mueller A. (2009) Determination of construction and demolition recycled aggregates composition, in considering their heterogeneity. Materials and Structures 42:739–748

[5] Cartz, L. (1995). Nondestructive Testing. A S M International

[6] Charles Hellier (2003). Handbook of Nondestructive Evaluation. McGraw-Hill.

[7] Coni M, Rombi J, Zedda V, Portas S, Pistis S (2012), Monitoring the Performances in Real Working Conditions of C&D Waste Materials in Road Construction Using Embedded Instruments, PET Journal

[8] Das A. (2010) Interpretation of Falling Weight Deflectometer data

[9] Della Rizza N. (2010) Thesis: Prove non distruttive con correnti parassite e magnetoscopia: applicazioni e analisi dei risultati, University of Padua

[10] Dowding, C.H. & O'Connor, K.M. (2000) "Comparison of TDR and Inclinometers for Slope Monitoring". *Geotechnical Measurements—Proceedings of Geo-Denver2000*: 80–81

[11] Vorster J and Gräbe H (2013) A new test track at the University of Pretoria : railway and harbour engineering, Civil Engineering = Siviele Ingenieurswese, Vol 21, Issue 4, 35-39

[12] Graveen C. (2001) Non-destructive test methods to assess pavement quality for usr in a performance-related specification, University of Purdue

[13] Jiménez J R (2013) Recycled aggregates (RAs) for roads, Handbook of recycled concrete and demolition waste, Cambridge UK

[14] Marradi A and Marvogli M, (2007) Falling Weight Defelctometer measurements for evaluation of bearing capacity of granular unbound layers, 4th INTERNATIONAL SIIV CONGRESS – PALERMO (ITALY), 12-14 SEPTEMBER

[15] Martìn-Morales M, M. ZAMORANO, I. VALVERDE-PALACIOS, G. M. CUENCA-MOYANO and Z. SÁNCHEZ-ROLDÁN , Quality control of recycled aggregates (RAs) from construction and demolition waste (CDW), Handbook of recycled concrete and demolition waste, Cambridge UK, 2013

[16] Poon C.S., Yu A. T.W., Ng L.H. (2001) On-site sorting of construction and demolition waste in Hong Kong, Resources, Conservation and Recycling 32 157–172

[17] Richardson A E, (2013) Strength and durability of concrete using recycled aggregates (RAs),Handbook of recycled concrete and demolition waste, Cambridge UK

[18] Rombi J., Coni M., Portas S. (2012) Experimental investigation on the use of C&DW materials as aggregates for road sub-base. PEAT Journal 13: 49-58

[19] Steyn W. JvdM, (2011) Applications of Nanotechnology in Road Pavement Engineering, Nanotechnology in Civil Infrastructure

[20] Stryk and Pospil, (2009) Non-destructive testing of pavement conditions (presentation CERTAIN workshop Tallinn)

[21] Theyse, H L and Muthen, (2000) M., Pavement analysis and design software (PADS) based on the South African mechanistic-empirical design method. CSIR Transportek , Pretoria, South Africa

[22] Theyse H.L. (2008). The Classical South African Mechanistic-Empirical Design Method. Pavement Modelling Corporation, Pretoria. Flexible pavement design course. Session 2: Structural capacity analysis. Module 3: Mechanistic-empirical design.

[23] Vorter D. J, (2012) The use of ground penetrating radar for track substructure characterization

[24] Daniels DJ (ed.) (2004). *Ground Penetrating Radar* (2nd ed.). Knoval (Institution of Engineering and Technology). pp. 1–4. ISBN 978-0-86341-360-5.

[25] Obrzud R. & Truty (2012) A.THE HARDENING SOIL MODEL - A PRACTICAL GUIDEBOOK Z Soil.PC 100701 report, revised 31.01.2012

[26] Kezdi, A. (1974). Handbook of Soil Mechanics. Elsevier, Amsterdam.

[27] Prat, M., Bisch, E., Millard, A., Mestat, P., and Cabot, G. (1995). La modelisation des ouvrages. Hermes, Paris.

Chapter 6

6 Conclusions

6.1 Conclusions

The study of C&D waste in the Durban Metropolitan Area has shown potential for reusing as aggregate for road construction from the quantitative and qualitative point of views. The Bisasar Road landfill site, as the largest in the Durban Metropolitan Area and one of the bigger in South Africa, was taken as a case study for understanding the amount of incoming waste. The data analysis of this landfill has shown significant quantities of C&D waste material coming from the entire area reaching the 50% of the total amount of incoming waste. The figure may be revised since not the all entire C&D waste arrives to landfill sites. The lack of knowledge, indeed, leads to unloading the waste to “free spaces” such as store area, which are not registered, or even discard in illegal dumps.

The geomechanical properties of C&D materials were checked. Tests on C&D waste material from Bisasar Road landfill site and from the deconstruction of an ex-military area were performed. They show its adaptability for replacing natural aggregates for road construction. The non-plasticity, the high water absorption and a good CBR are generally the main characteristics. This kind of aggregates is commonly index-linked as A1a according to HRB Classification by AASTHO. The more complex soil classification system used in South Africa allows being more accurate, the studies done so far have reported indices that are equivalent to natural aggregates ranging from G3 (materials from deconstruction) to G6 (materials from landfill). This highlights the heterogeneity of C&D materials. When the waste from construction and demolition come from different places and is stored in landfills it is often mixed up giving lower grade materials. However if these are carefully separated, as in the case of a deconstruction, it is possible to obtain more homogeneous materials with less contamination due to impurities such as wood, carpet, plastic, glass. In fact, the results of masonry and concrete derived from the demolition of walls and foundations have shown variability in test results lower than 15%.

The durability tests for these materials shows higher loss of weight percentage than natural aggregates and it may be considered as a weakness. It was observed a direct correlation between water absorption with Los Angeles Abrasion test and with Aggregate Crushing Value. In particular water absorption higher than 6% most likely does not comply with the standards suggested for road pavements aggregates. However tests performed on samples subjected to repeated cycles of wet-dry conditions demonstrate that a long term decay of the strength characteristics is not expected for this material.

Chemical analysis were also performed on the leachate of these materials and proved the absence of hazardous components in terms of concentrations prescribed by the EU standards. As such, no additional rehabilitation treatment is required on these materials before their use in the field.

A blend of concrete and masonry, with characteristics of G4 aggregates, was used for the construction of an experimental and instrumented embankment which was observed for 10 months. The monitoring on this test-bed was performed in two different ways, one with in situ test and the other by sensors embedded inside the embankment. Its behaviours demonstrated similarity to natural aggregates in real working condition; layers are more compacted due to consolidation and the transit of the truck. Different methods were used to calculated Young's modulus: the triaxial test in laboratory, the FWD test on the surface, the embedded LVDTs and pressure cells which results are used for the backcalculation with South African software mePads. Different results were reached since the boundary conditions and methodology were not the same. It was interesting the use of embedded sensors which allow a monitoring in the entire embankment. Even with this test the C&D material used in the test bed shows G4 characteristics.

6.2 Recommendations

The use of C&D waste for road construction is strongly recommended even in South Africa, but some recommendations should be followed.

- A better management of the incoming C&D waste is suggested. The case study of Bisasar Road landfill site demonstrates that it may be implemented without a drastic alteration of the collection and storage system already in use. Moreover a detailed study of the road metropolitan network, landfill sites, position and dimension of construction sites can help to develop a system for C&D waste disposal at intermediate stockpiling areas to encourage the reuse of C&D materials wherever applicable.

- In the landfills or in storage areas, keeping C&D waste material in different stockpiles according to its nature and gradings help to reduce its heterogeneity and then to simplify its recycling and its reuse. Moreover, by avoiding the collection of C&D waste at only a small number of landfill areas, the economic and environmental cost of its transport can be reduced.
- The results of tests performed on concrete, masonry and a mix of the two of them suggest the use for unbound bases and sub-bases layers according to South African specifications and recommended for unbound layers when designs follow the AASHTO specifications.
- Although C&D materials have high values of the durability test compared to natural aggregates, concrete, masonry and blend with various moisture condition (wet-dry test) make evident that a long term decay of the strength characteristics is not predictable.
- A material with similar characteristics to G4 and obtained from a mix of masonry and concrete is recommended for application in real working condition. Its behaviours are similar to natural aggregates, and the elastic modulus increased that demonstrates good strength properties.

UNIVERSITY OF KWAZULU-NATAL
INYUVESI YAKWAZULU-NATALI

Appendix A

Name of interviewer____________________
Date____________________
Number____________________

QUESTIONNAIRE
On Construction and Demolition waste

A. General ID of vehicle

1. Type of vehicle Car Bakkie (LDV) Truck Other________________________

2. Registration of vehicle ____________________________

B. Weigh-bridge data

3. Are you a...? Contractor Private

If contractor Name of company ______________ Base_______________________________

4. What kind of C&D waste are you transporting?

landfill site classification: Rubble Sand and cover material Purchase
Specify____

5. Estimation of material quantity being delivered

____

6. Were you charged for disposal of C&D material?

____

7. Where is it dumped?

____

C. Driver questionnaire

8. Where are you transporting C&D from?

Is the material only from ONE site? If not, please indicate ALL the origins

City\Town ____________________Suburb _________________ Street __________________

City\Town ____________________Suburb _________________ Street __________________

City\Town ____________________Suburb _________________ Street __________________

9. What type of site does the material come from?

SITE 1 Road Sidewalk House Shop Factory

Other_____________________

SITE 2 Road Sidewalk House Shop Factory

Other_____________________

SITE 3 Road Sidewalk House Shop Factory

Other_____________________

10. Will there be more loads from this site? YES NO

SITE 1 Road Sidewalk House Shop Factory

Other_____________________

SITE 2 Road Sidewalk House Shop Factory

Other_____________________

SITE 3 Road Sidewalk House Shop Factory

Other_____________________

Appendix B

GRANULAR BASES (MODERATE OR DRY REGIONS) DATE 1996

PAVEMENT CLASS AND DESIGN BEARING CAPACITY (80 kN AXLES/LANE)

ROAD CAT.	ES0.003 < 3000	ES0.01 $0,3\text{-}1,0x10^4$	ES0.03 $1,0\text{-}3,0x10^4$	ES0.1 $3,0\text{-}10x10^4$	ES0.3 $0,1\text{-}0,3x10^6$	ES1 $0,3\text{-}1,0x10^6$	ES3 $1,0\text{-}3,0x10^6$	ES10 $3,0\text{-}10x10^6$	ES30 $10\text{-}30x10^6$	ES100 $30\text{-}100x10^6$	Foundation
A							40A 125 G2 150 C3 40A 150 G2 150 G5	40A 150 G2 250 C3	50A 150 G1 250 C3	50A 150 G1 300 C3	
B						S 125 G4 150 C4 S 150 G4 150 G5	S*/30A 150 G3 150 C4 S*/30A 150 G3 150 G5	40A 150 G2 200 C4 30A 150 G2 200 G5			150 G7 150 G9 G10
C				S 100 G5 125 C4 S 125 G4 125 G6	S 125 G5 125 C4 S 125 G4 150 G6	S 125 G4 125 C4 S 125 G4 150 G5	S 150 G3 150 C4 S 150 G3 150 G5				
D	S1 100 G5 100 G7	S1 100 G5 125 G7	S1 100 G4 125 G7	S1 100 G4 125 G6 S1 100 G5 100 C4	S 125 G4 125 G6 S 100 G5 125 C4	S 125 G4 150 G6 S 125 G5 150 C4					150 G9 G10

Symbol A denotes AG, AC, OR AS. A0, AP may be recommended as a surfacing measure for improved skid resistance when wet or to reduce water spray.
S denotes Double Surface Treatment (seal or combinations of seal and slurry)
S1 denotes Single Surface Treatment
* If seal is used, increase C4 and G5 subbase thickness to 200mm.

GRANULAR BASES (WET REGIONS)

DATE 1996

PAVEMENT CLASS AND DESIGN BEARING CAPACITY (80 kN AXLES/LANE)

ROAD CAT.	ES0.003 < 3000	ES0.01 $0,3-1,0 \times 10^{4}$	ES0.03 $1,0-3,0 \times 10^{4}$	ES0.1 $3,0-10 \times 10^{4}$	ES0.3 $0,1-0,3 \times 10^{6}$	ES1 $0,3-1,0 \times 10^{6}$	ES3 $1,0-3,0 \times 10^{6}$	ES10 $3,0-10 \times 10^{6}$	ES30 $10-30 \times 10^{6}$	ES100 $30-100 \times 10^{6}$	Foundation
A							30A 150 G1** 200 C3	40A 150 G1 300 C3 *(250 C3)	50A 150 G1 400 C3 *(300 C3)		
B						S 150 G2 150 C4 S 150 G2 200 G5	S/30A 150 G1** 200 C4	40A 150 G1 300 C4 *(250 C4)			150 G7 150 G9 G10
C				S 100 G5 125 C4 S 125 G4 125 G6	S 125 G5 125 C4 S 150 G4 150 G6	S 125 G2 150 C4 S 150 G2 150 G5	S 150 G2** 200 C4 S 150 G2 150 G4				
D	S1 100 G5 100 G7	S1 100 G5 125 G7	S1 100 G4 125 G7	S1 100 G4 125 G6 S1 100 G5 100 C4	S 125 G4 125 G6 S 100 G5 125 C4	S 150 G4 150 G6 S 125 G5 150 C4					150 G9 G10

Symbol A denotes AG, AC, OR AS. A0, AP may be recommended as a surfacing measure for improved skid resistance when wet or to reduce water spray.
S denotes Double Surface Treatment (seal or combinations of seal and slurry)
S1 denotes Single Surface Treatment
* If water is prevented from entering the base, the subbase thickness may be reduced to the values indicated in brackets.
** Base thickness may be reduced by 25 mm if cemented subbase thickness is increased by 50 mm.

HOT-MIX ASPHALT BASES

DATE 1996

PAVEMENT CLASS AND DESIGN BEARING CAPACITY (80 kN AXLES/LANE)

ROAD CAT.	ES0.003 < 3000	ES0.01 $0,3-1,0 \times 10^{4}$	ES0.03 $1,0-3,0 \times 10^{4}$	ES0.1 $3,0-10 \times 10^{4}$	ES0.3 $0,1-0,3 \times 10^{6}$	ES1 $0,3-1,0 \times 10^{6}$	ES3 $1,0-3,0 \times 10^{6}$	ES10 $3,0-10 \times 10^{6}$	ES30 $10-30 \times 10^{6}$	ES100 $30-100 \times 10^{6}$	Foundation
A							40A 80 BC 250 C3	40A 90 BC 300 C3	40A 120 BC 400 C3	50A 180 BC 450 C3	
B							30A 80 BC 200 C4	30A 80 BC 300 C3			150 G7 150 G9 G10
C											
D											

Symbol A denotes AG, AC, OR AS. A0, AP may be recommended as a surfacing measure for improved skid resistance when wet or to reduce water spray.
Symbol BC does not include LAMBS (BC1 Table 13)
S denotes Double Surface Treatment (seal or combinations of seal and slurry)
S1 denotes Single Surface Treatment

CEMENTED BASES

DATE 1996

ROAD CAT.	PAVEMENT CLASS AND DESIGN BEARING CAPACITY (80 kN AXLES/LANE)										Foundation
	ES0.003 < 3000	ES0.01 $0,3\text{-}1,0 \times 10^4$	ES0.03 $1,0\text{-}3,0 \times 10^4$	ES0.1 $3,0\text{-}10 \times 10^4$	ES0.3 $0,1\text{-}0,3 \times 10^6$	ES1 $0,3\text{-}1,0 \times 10^6$	ES3 $1,0\text{-}3,0 \times 10^6$	ES10 $3,0\text{-}10 \times 10^6$	ES30 $10\text{-}30 \times 10^6$	ES100 $30\text{-}100 \times 10^6$	
A							30A 150 C3 200 C4				
B						S 125 C3 150 C4	S 125 C3 200 C4	S/30A 150 C3* 300 C4			150 G7 150 G9 G10
C				S 100 C4 100 G6	S 200 C3 S 125 C4 125 G6	S 125 C3 125 C4	S 150 C3 150 C4				
D	S1 100 C4 100 G8	S1 100 C4 125 G8	S1 125 C4 125 G7	S1 150 C4 150 G7	S 125 C4 125 G6	S 125 C4 150 G6					150 G9 G10

Symbol A denotes AG, AC, OR AS. A0, AP may be recommended as a surfacing measure for improved skid resistance when wet or to reduce water spray.
S denotes Double Surface Treatment (seal or combinations of seal and slurry)
S1 denotes Single Surface Treatment
* Crushing of cemented base may occur

WATERBOUND MACADAM BASES

DATE 1996

ROAD CAT.	PAVEMENT CLASS AND DESIGN BEARING CAPACITY 80kN/LANE										Foundation
	ES0.003 < 3000	ES0.01 $0,3\text{-}1,0 \times 10^4$	ES0.03 $1,0\text{-}3,0 \times 10^4$	ES0.1 $3,0\text{-}10 \times 10^4$	ES0.3 $0,1\text{-}0,3 \times 10^6$	ES1 $0,3\text{-}1,0 \times 10^6$	ES3 $1,0\text{-}3,0 \times 10^6$	ES10 $3,0\text{-}10 \times 10^6$	ES30 $10\text{-}30 \times 10^6$	ES100 $30\text{-}100 \times 10^6$	
A#							30 - 40A* 125 WM1 150 C3	40A* 150 WM1 125 C3 125 C4	50A* 150 WM1 150 C3 150 C3		
B					S* 100 WM2 150 G5	S* 125 WM2 150 G5	S or 30A* 125 WM2 150 C4	40A* 125 WM1 125 C4 125 C4			150 G7 150 G9 G10
C				S* 100 WM2 100 C4 S* 100 WM2 125 G5	S* 100 WM2 125 C4	S* 100 WM2 150 G5	S* 125 WM2 100 C4 S* 125 WM2 150 G5				
D											

* SYMBOL A DENOTES AG, AC, OR AS. SYMBOL S DENOTES S2 OR S4 , SEE TABLE 13 FOR MATERIAL SYMBOLS PM = PENETRATION MACADAM.
FOR SELECTED LAYERS REFER TO PARAGRAPH 8.4.2: FOR FUTURE MAINTENANCE TO PARAGRAPH 9.5.
A0, AP PERMITTED AS A SURFACING MEASURE FOR SKID RESISTANCE OR REDUCTION OF WATER SPRAYING.
\# FOR CATEGORY A PAVEMENTS CONSTRUCTED WITHOUT PAVERS, AN ASPHALT LEVELING COURSE OF 25mm to 30mm IS NORMALLY NEEDED TO IMPROVE RIDING QUALITY.