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LIST OF ABREVIATIONS

AASHTO	American Association of State Highway and Transportation Officials
ASTM	American Society for Testing and Materials
BNQ	Bureau de normalisation du Québec
C	Coarse
CBR	California Bearing Ratio
CD	Consolidated-Drained
CFL	Coarse limestone
CG	Crushed glass
CO2	Carbon dioxide
CRG	Coarse Recycled Glass
CT	Computed tomography
CU	Consolidated-Undrained
CWC	Clean Washington Center
DM	Dredged materials
ÉTS	École de Technologie Supérieure
F	Fine
FFL	Fine limestone
FHWA	Federal Highway Administration
FL	Fine fraction of limestone aggregate (0-5mm
FRG	Fine Recycled Glass
H	High
IJPE	International Journal of Pavement Engineering
K	Kaolinite
LA	Los Angeles abrasion test
LCMB	Pavement and Bituminous Materials Laboratory
L	Low
LVDT	Linear variable differential transducers
M	Medium
MFL	Medium limestone

MRG	Medium Recycled
MTMDET	Ministry of Transport, Urban Mobility and Electrification of Transportation of Quebec
Na_2Co_3	Sodium carbonate
NCHRP	National Cooperative Highway Research Program
QF	Quarry fines
RAP	Recycled asphalt pavement
RCA	Recycled concrete aggregate
RG	Recycled glass
RMSE	Root-mean-square error
R-Value	Resistance -Value
Sio_2s	Silicon dioxide
SP	Poorly graded sand
SP-SW	Poorly graded SAND with silt
SW	Well-graded sand
SWCC	soil-water characteristic curves
TAC	Transportation Association of Canada
USCS	Unified Soil Classification System
VF	Very fine
VFFL	Very fine limestone
VFRG	Very fine recycled glass
WR	Waste rock

LIST OF SYMBOLS

%	Percent
°	Degree
Δ	Difference between the measured and predicted M_r
γ_d	Dry unit weight
γ_{dMAX}	Maximum dry density
$\gamma_{dLimestone}$	Dry unit weight of limestone
γ_{dMAX}	Maximum dry unit weight
$\gamma_{dRecycled\ glass}$	Dry unit weight of recycled glass
$\rho_{dLimestone}$	Dry density of limestone
ρ_{dMAX}	Maximum dry density
ρ_{dn}	Normalized dry density of specimen
$\rho_{dRecycled\ glass}$	Dry density of recycled glass
λ	Pore-size distribution index
$\frac{\nu_{10}}{\nu_T}$	Viscosity ratio of water
ν_w	Viscosity of water (Pa.s)
θ	Bulk Stress (Equation 6.2 and 6.3)
θ	Volumetric water content at any suction (Equation 4.1)
θ_s	Saturated volumetric water content,
θ_r	Residual water content
ρ_s	Particle density
σ_3	Confining Stress
σ_d	Deviatoric Stress
ψ	Soil suction
ψ_a	Air-entry value of the soil
ψ_r	Suction corresponding to the residual water content
A	Cross section of specimen
a	Suction related to the air-entry value of the soil
C_0	Constant for smooth rounded and irregularly shaped grains

C_c	Coefficient of curvature
Cm	Centimeter
C_u	Coefficient of uniformity
$C(\psi)$	Correction function
d	Size of particle
D_{10}	Particle diameters corresponding to 10% finer on the cumulative particle-size distribution curve
D_{30}	Particle diameters corresponding to 30% finer on the cumulative particle-size distribution curve
D_{60}	Particle diameters corresponding to 60% finer on the cumulative particle-size distribution curve
e	Natural number, 2.718 28
e	Void ratio
e_{max}	Max void ratio
eV	Electronvolt
G_s	Specific gravity
g	Gravitational constant
H	Difference in head of manometers
in	Inch
K	Hydraulic conductivity
$\mathrm{k}_1, \mathrm{k}_2$	Regression coefficients
Kg	Kilogram
$kN/_{m^3}$	Kilonewton per cubic meter
kPa	Kilopascal
K_{sat}	Saturated hydraulic conductivity
L	Distance between manometers
m	Soil parameter related to the residual water content
MG20	Size gradation envelope, which is specified for the base course according to MTMDET
mm	Millimeter

MPa	Megapascal
M_r	Resilient modulus
n	Soil parameter related to the slope at the inflection point on the SWCC
P	Mean Stress
P_a	Atmospheric pressure, $100kP$
Pa	Pascal
$P_{Limestone}$	Proportion of limestone in the blend
$P_{Recycled\ glass}$	Proportion of recycled glass in the blend
q	Deviatoric stress
Q	Quantity of water discharged
s	Second
S_S	Surface specific (m^2/kg)
S_{sf}	Specific surface areas of fines expressed in $\frac{m^2}{g}$
t	Total time of discharge
T	Temperature
W_{OPT}	Optimum water contents

INTRODUCTION

0.1 Research problems and motivation

As the size of the world's population has grown, waste creation has increased rapidly. Plenty of waste materials produced today will remain in the environment for hundreds of years. The creation of non-decaying waste, combined with a growing population of consumers, has resulted in a waste disposal crisis. One possible solution to this coming crisis lies in recycling such waste into valuable products (Reid et al., 2001).

In Quebec, recycling is done through a selective collection. All recyclable materials including carton, paper, glass, and others are collected quickly and in an uncontrolled way from the bins by the selective collection and sent to the sorting centers by truck. In this way the glass breaks in the bin or in the transport and is contaminated (Caillou, 2017). At the sorting center, coarse glass is separated from other materials by manual sorting where possible. Glass pieces that are too small and cannot be sorted manually are mixed together. The combination of several types and colors of glass is called mixed glass. Furthermore, the mixed glass contains of a few numbers of other materials including plastic, paper, and others. The industry of glass recycling remains a challenge in Quebec due to some problems, which are explained more as follows:

(1) New product of glass requires the separation of glass by colors as well as the removal of any debris stuck to the glass (Taha & Nounu, 2008). The high cost of the complicated processes that is required for separating the different colors of mixed glass is an obstacle for producing new glass. Therefore, this contaminated and mixed-color glass results in a low added-value usage like ending up in the landfills (RECYC-QUÉBEC, 2012).

(2) In 2013 the low economic value of glass eventually led to the closure of the main glass processing plant in Quebec. It was the only company in Quebec with the

capacity to process large volumes of clean glass and also to process mixed glass from selective collection (RECYC-QUÉBEC, 2012).

Some research projects are underway to find the new added-value applications for mixed glass. These applications are divided into two categories namely low added-value application and high added-value application. In 2015, 67% of the amount of mixed glass recycled in the province of Quebec was allocated for low added-value applications such as backfill material in landfills (compared to 57% in 2014). However, the proportion of glass sent to recycling companies fell to 25% from 37% in 2014, for high added-value application like glass wool or as an additive to the cement mix used to make concrete (Recyc-Québec, 2014, 2015). According to an estimate by Éco Entreprises Québec, the recycling rate for glass could increase to 54% by 2019, as new glass sorting and cleaning equipment is being tested in some sorting centers in Quebec (Caillou, 2017). Finding an innovative approach of reusing glass can help to increase the high added-value application of mixed glass. Geotechnical engineering applications and especially roadwork applications have become one of the most attractive fields of reusing such materials. However, it is important to notice that the use of such materials should not lead to decrease either the bearing capacity or the life cycle of roads (Rabaiotti & Caprez, 2005). Several research projects concerning the recycling of glass aggregates in pavement materials were carried out at the Pavement and Bituminous Materials Laboratory (LCMB) of the École de Technologie Supérieure (ÉTS). This thesis is devoted to using recycled glass (RG) as a replacement for aggregate in pavement structures, which can be a solution for the problems of glass recycling in Quebec.

The research studies so far by various researchers around the world reveal that, although RG is recognized to have many applications such as drainage and backfill, the limited knowledge concerning the engineering characteristics has slowed down its reuse potential (Wartman et al., 2004a). Furthermore, in the published regulations and specification of the Ministry of Transport, Urban Mobility and Electrification of Transportation of Quebec (MTMDET), there is not any permission of using RG in various roadwork applications as a replacement of natural aggregate. Nevertheless, using some recycled materials in the roadwork such as asphalt or concrete, concrete brick, and clay brick, are authorized by Bureau de normalisation du Québec (BNQ) (BNQ, 2002). Hence, the shortage of knowledge on precise characteristics of RG motivates the author to investigate the geotechnical performance of RG as granular base aggregate and to fill the gap on the geotechnical characteristics. The main objective of this research is to enhance the high-added value usage of RG through studying the advantages and boundaries of using RG in granular materials of the pavement structure, namely base course. The focus of this research is to investigate the hydraulic and mechanical aspects of using RG in base course, which has major roles in the performance of base course structure as discussed in the chapter of literature review.

0.2 Structure of work

This dissertation includes series of published and submitted technical papers related to the general objectives of this research, namely the investigation of the effects of using RG on the hydraulic and mechanical behavior of unbound granular materials of the pavement structure. The program was divided into three parts. The first part was studying the physical and hydraulic properties of the separate sizes of RG and crushed limestone aggregate. In the second and third parts, the experimental tests were applied to trace the impact of utilizing RG blends with limestone as the unbound granular materials on the performance of pavement structures. A wide range of geotechnical laboratory testing was analyzed to find conclusive evidence for the use of blends of this recycled material in road applications.

Since it is a thesis by publication, the experimental results have been submitted for publication in scientific journals. These articles are integrated into the body of this document right after the literature review, and the objectives of this research project. A discussion on the obtained results and the conclusion are presented after the different papers, before giving some recommendations.

CHAPTER 1

LITERATURE REVIEW

A review of the relevant literature was conducted to satisfy the objectives of this study. As mentioned earlier, the format of this dissertation is a series of accepted or submitted journal papers with the scope of the investigation of using recycled glass (RG) in unbound granular materials of the pavement structure. Chapter 1 includes five sections related to first, using RG as granular base aggregate, followed by physical, hydraulic and mechanical aspects of using glass aggregate in roadwork application and the related testing methods, and in the end blends of RG with other materials. The information specified in this chapter aims to demonstrate the findings and efforts related to the scope of this dissertation.

1.1 Introduction to using RG as granular aggregate in base course

Supercooling of a melted liquid mixture consisting of silicon dioxide, SiO_2, and sodium carbonate, Na_2CO_3, to a rigid condition produces glass. In the mentioned phenomenon the produced material does not crystallize and hold the structure of melted liquid (FHWA, 1998). The common glass contains about 70% SiO_2 in which Na_2CO_3 acts as a fluxing agent in the production process. Other additives are also used in producing glass to obtain specific properties, and different iron compounds are applied as coloring agents (FHWA, 1998). The glass is categorized into various types based on its chemical properties including binary alkali-silicate glass, borosilicate glass, and soda-lime silicate glass (Shayan & Xu, 2004). Window glass and glass bottles are in the subcategory of soda-lime silicate glass, which is composed of 70 to 73 percent of SiO_2. The typical compositions of soda-lime silicate glass are presented in Table 1-1 based on FHWA (1998). The different kinds of glass bottles that are the case of this study are manufactured in various colors, mostly green, amber, and clear.

Table 1-1 Typical chemical composition of soda-lime silicate glass adapted from FHWA (1998, p. 20-6)

Constituent	**Soda-lime silicate**
SiO_2	70-73
Al_2O_3	1.7-2.0
Fe_2O_3	0.06-0.24
Cr_2O_3	0.1
CaO	9.1-9.8
MgO	1.1-1.7
Na_2O	13.8-14.4
K_2O	0.55-0.68

All kinds of glass can be indefinitely recycled because it can retain the similar properties of the reference glass used in the manufacture (Gagné, 2010). However, using RG in manufacturing new glass needs to separate glass by colors. The mixed glass is proposed to be used in other applications including concrete aggregate, fiberglass insulation, road work, or sent to the landfill (Shayan & Xu, 2004). The ever-increasing rate of disposal materials highlights the requirement of recycling more waste materials to reduce the demand for landfills and primary natural resources (Halstead, 1993). Hence, achieving innovative methods of reusing million tons of such materials is a widespread goal (Taha & Nounu, 2008). One of the most practical methods among new ways of reusing waste materials is applying them in roadwork especially in unbound layers of the pavement structure.

Pavement structures include three layers, subgrade, aggregate base/subbase and surfacing layer. The base course is a layer of aggregate that lies below surfacing layers and usually consists of crushed aggregate or recycled material (White et al., 2004). According to Dawson (Dawson, 1995), the important roles of base course aggregate in pavements include the following items:

(1) Protecting subgrade from significant deformation because of traffic loading and against frost and environmental damage
(2) Providing sufficient support for the surface layer
(3) Providing a stable construction platform during pavement surfacing
(4) Providing adequate drainage of moisture that enters in pavement structure

Since the unbound layers of pavement play a principal role in the structural capacity and also the drainage of excess water, investigating both mechanical and hydraulic characteristics of the blends of RG with common unbound aggregate is essential. The following sections of this thesis will focus on the different aspects of using RG in the unbound granular aggregate of base course.

Specific engineering properties become important for each application of RG. Table 1-2 shows some applications of RG and the level of importance for material properties and engineering characteristics. In the case of base and subbase materials, the pure RG or RG blended with natural aggregate needs to meet the minimum standards required and specified by road authorities. From Table 1-2 it can be seen that achieving the engineering characteristics, including permeability and shear strength, is identified as the high level of importance for base and subbase applications.

1.2 Environmental assessment and physical aspects

The different kind of debris in RG including ceramics, metals, organic and other inorganic materials, cause environmental concerns (Disfani et al., 2012). Various types of debris or contaminants in glass particles as construction materials are recommended to be restricted to 5% (CWC, 1998). The Clean Washington Centre (CWC, 1998) investigated the environmental suitability of RG as construction material. The chemical properties of glass are in appropriate ranges without any problem for construction aggregate users (CWC, 1998). Also, the results of study on leaching tests of glass by Wartman et al. (2004b) showed that there is no hazardous contamination in glass.

Table 1-2 Civil engineering application of RG and level of importance for material properties and engineering characteristics, Adapted from CWC (1998, p. 6)

		Material properties				Engineering characteristics	
Application	**Description**	**Specific gravity**	**Gradation**	**Workability**	**Durability**	**Permeability**	**Shear strength**
General backfill	Non-loaded conditions	H	H	H	L	L	L
	Fluctuating loads	H	H	H	H	L	H
	Heavy, stationary loads	H	H	H	L	L	H
Roadways	Base, subbase	H	H	H	H	H	H
	Embankments	H	H	H	L	L	H
Utilities	Pipe trench bedding/backfill	H	L	H	L	L	L
	Conduit bedding & backfill	H	L	H	L	L	L
	Filter optic cable bedding & backfill	H	L	H	L	L	L
Drainage	Foundation design	H	H	H	L	H	L
	Drainage blanket	H	H	H	L	H	L
	French drains	H	H	H	L	H	L
	Septic fields	H	H	H	L	H	L
	Leachate treatment	H	H	H	L	H	L
Miscellaneous	Landfill cover	H	L	H	L	L	L
	Underground tank fill	H	L	H	L	L	L

H=High

L=Low

Various factors influence the geotechnical characteristics of RG provided by different suppliers (Disfani et al., 2011a). For instance, the processing equipment, procedures of crushing and sieving of different suppliers are not similar. Hence, this difference influences the size gradation and debris level of product which consequently affects the geotechnical characteristics of RG from one supplier to another (Disfani et al., 2011b). Crushed glass particles are generally angular and can contain some flat and elongated particles. The degree of angularity and the quantity of flat and elongated particles depend on the degree of processing and crushing (FHWA, 1998).

1.3 Hydraulic aspect

The sources of moisture in pavement systems include capillary rise from the water table, infiltration of moisture from precipitation and lateral moisture transfer (Doré & Zubeck, 2009). The presence of moisture in base and subbase materials influences the bearing capacity of pavements. Seasonal variations of moisture content in the pavement layer affect pavement performance due to freeze-thaw cycles (Côté & Konrad, 2003). Furthermore, repeated wheel loads on a saturated base can generate excessive pore-water pressure and result in the loss of support and stability of the structural layers (Dawson, 1995). The pavement system is subjected to differential frost heaving during winter due to formation of ice lenses and ice within the soil matrix immediately below the pavement structure. Also, the pavement system experiences thawing during spring break-up period that results in melting frost (Côté & Konrad, 2003).

Good drainage capacity of granular materials is necessary to remove any excess water and minimize pavement damages due to moisture (Côté & Konrad, 2003). Hence, a good understanding of the drainage characteristics of base aggregate is important for the design and performance evaluation of pavements (Dawson, 1995). In Quebec, based on the specifications of MTMDET, the fines (particles smaller than 0.08 mm) of base course aggregate should not exceed 7% to preserve adequate bearing capacity, ensure good drainage, and limit frost action damage. Among all factors affecting the movement of water in pavement structures, the hydraulic conductivity and the soil-water characteristic curves (SWCC) of construction materials are the most important parameters (Alonso, 1998). The next sections present an overview of parameters affecting the hydraulic conductivity as well as the SWCC of granular base course materials, then previous research on the hydraulic aspect of RG.

1.3.1 Hydraulic conductivity

Hydraulic conductivity of a soil is the ability of material to transfer moisture (FHWA, 2006). Hydraulic conductivity of base layers is an important consideration for water movement, drainage and pavement service life (Apul et al., 2002).

The hydraulic conductivity is determined based on the measured head loss, cross section of the sample and flow rate of water through the sample, as the following formula (ASTM, 2006):

$$K = \frac{QL}{Ath} \tag{1.1}$$

Where:

k = hydraulic conductivity (m/s),
Q = quantity of water discharged,
L = distance between manometers,
A = cross section of specimen,
t= total time of discharge,
h = difference in head of manometers.

The hydraulic conductivity must be corrected to that for 20^{0C} by multiplying k by the ratio of the viscosity of water at test temperature to the viscosity of water at 20^{0C} (ASTM, 2006).

It is generally assumed that the hydraulic conductivity of aggregate is influenced by the size, shape, texture, and configuration of the particles, by tortuosity of flow, and by the dynamic viscosity, and the density of the permeant (Murray, 1995). The saturation degree also affects the hydraulic conductivity of a soil (Richardson, 1997). The comparison of many hydraulic conductivity values needs to be done for a unique degree of saturation, which is usually set to 100%. Côté et Konrad (2003) and Ghabchi et al., (2014) showed that the hydraulic conductivity of base course aggregate is significantly affected by the overall porosity and the fines content. Increasing porosity and decreasing fines content lead to increasing hydraulic conductivity values of base course aggregate (Ghabchi et al., 2014).

Previous studies of hydraulic conductivity on RG did not reveal consistent results. The value of hydraulic conductivity of glass is reported between 0.000161 cm/s and 0.26 cm/s (Disfani et al., 2012; FHWA, 1998; NCHRP, 2003; Pennsylvania, 2001; Wartman et al., 2004a). The remarkable diversity in the hydraulic conductivity of glass obtained from different research is because of the difference in gradation curves of glass and fines.

1.3.2 Soil water characteristics curve (SWCC)

Water retention capacity of base course material is also important to evaluate the drainability of pavement system (Tandon & Picornell, 1997). In rainfall events, when moisture fills the pores of pavement, the water flows downward under gravity gradient. Afterward, some proportions of pores in the base course begin to be desaturated with water under negative pressure. This process leads into an unsaturated system with residual moisture (Apul et al., 2002). Soil water characteristics curve (SWCC) describes the relationship between matric suction at which air begins to enter into the material and water content. Base course material can be considered either as in saturated state or unsaturated state. In unsaturated state, the intergranular void space between aggregate is filled with water and air. The ability of such criterion to allow the flow of water through the particles can be expressed by unsaturated hydraulic conductivity. The hydraulic conductivity in unsaturated state is dependent on the degree of saturation or volumetric water content (Côté & Konrad, 2003).

The matric suction of a soil is dependent on the pore diameter (Marshall, 1959). Therefore, the air entry pressure of a soil reflects the maximum pore size of a soil. It means that the values of air entry pressure increases with decreasing porosities (Craciun, 2009). Based on the literature review, no study on SWCC of RG was found.

1.4 Mechanical properties

As mentioned before in Table 1-2, the workability, durability and shear strength are in the high level of importance for base and subbase materials. In the following sections first, the background of the mentioned characteristics will be described, then the summary of literature review on RG in such aspects will be presented.

1.4.1 Workability

The workability of aggregate, which is significantly affected by the angularity and shape of particles, means the ease with which an aggregate is handled and compacted (CWC, 1998). One of the direct methods to assess the workability is identified by evaluating the compaction characteristics (CWC, 1998). The modified Proctor compaction method in the laboratory resembles the situation related to heavy impact field compaction equipment (Landris & Lee, 2007).

The compaction properties of RG based on previous works are presented in Table 1-3. As can be seen from the Table 1-3 the maximum dry density of glass for different research seems to be similar with a little difference because of various particle size distributions (Disfani et al., 2011b). The maximum dry density of glass is lower than natural granular material (FHWA, 1998). The sieve analysis after compaction tests on glass showed that the coarser ones (particle smaller than 9.5 mm) experience a greater reduction in particle size than finer (particle smaller than 4.75 mm) (Wartman et al., 2004a). Therefore, fine glass is stable mixture during handling, spreading and compaction (Disfani et al., 2011b).

1.4.2 Durability

Crushing and grinding of aggregate are expected to happen during mixing, transportation, placement and compaction (CWC, 1998). The previous researchers commonly used the Los

Angeles abrasion test (LA) to evaluate durability of RG aggregate and its blends against abrasion.

Table 1-3 Typical mechanical properties of glass

Reference	Compaction (modified): max dry density (Kg/m^3)		Optimum moisture (%)	California bearing ratio (%)	Los Angeles test (%)
(FHWA, 1998)	1800-1900		5.7-7.5	-	30-42
(Wartman et al., 2004a)	1750-1830		9.7-11.2	-	24-25
(Grubb et al., 2006b)	1870		8	-	-
(Ooi et al., 2008)	1850		9.7	75-80	27-33
(Disfani et al., 2012)	Smaller than 4.75mm	1750	10	42-46	24.8
	Smaller than 9.5 mm	1950	8.8	73-76	25.4

The summary of previous researches on durability of RG is described in Table 1-3. Based on previous research fine glass (smaller than 4.75 mm) (Disfani et al., 2012; Ooi et al., 2008; Wartman et al., 2004a) shows reasonable Los Angeles values compared to the amount indicated by road authorities for base materials, a maximum value of 35% (NCHRP, 2003).

1.4.3 Shear strength

Shear strength parameters give a suggestion for the prediction of the aggregate behavior under the effect of applied static and dynamic loads where the aggregate acts as load carrying medium (CWC, 1998). Since the primary load carrying is by aggregate medium, the inter-particle friction of aggregate influences mainly the shear strength. The factors contributing to inter-particle friction include surface texture, particle shape, void ratio or degree of compaction, and particle size gradations (CWC, 1998). The most common tests to indicate the shear strength parameters include direct shear test, triaxial shear, California Bearing Ratio (CBR), Resistance R-Value, and resilient modulus. The type of geotechnical engineering application indicates the test selection (Landris & Lee, 2007). For roadwork applications CBR and resilient modulus are considered as the usual and important tests, which are described in next sections.

1.4.3.1 CBR test

California Bearing Ratio (CBR) test is an indirect test for measuring shear strength. This test is a penetration test for evaluation of the mechanical strength of pavement subgrade, subbase, and base course materials from laboratory compacted specimens (FHWA, 2006).

The CBR values of RG samples based on previous study are presented in Table 1-3. As a comparison of CBR test results between glass and natural aggregate, glass showed smaller amount of CBR (Wartman et al., 2004a). A minimum CBR value of 100% is typically required for base course aggregate (NCHRP, 2003). Glass is a fragile material that breaks due to tensile stress and its gravel-sized particles (greater than 4.75mm) shows relatively poor durability in comparison with natural aggregate (FHWA, 1998).

1.4.3.2 Resilient modulus test

Granular layer plays an important role to distribute the traffic load through underlying layers and consequently to the overall performance of the pavement system. Therefore, understanding and considering the response of granular layers under traffic loading is important (Lekarp et al., 2000a). Under a passing wheel loading, a pavement experiences a complex stress pattern consisting of the vertical and horizontal (Figure 1-1). This can be represented by a change in both the major and minor principle stress components, plus a rotation of principal stress axis (Lekarp et al., 2000a). The deformation responses of granular materials under repeated loads are specified by a resilient response and a permanent strain response through triaxial repeated load tests for a high number of load cycles. Resilient response is important for the load-carrying ability of the pavement. Permanent strain response characterizes the long-term performance of the pavement and the rutting phenomenon (Lekarp et al., 2000b). Figure 1-2 presents a simple explanation of resilient and permanent strains in granular materials for one cycle of load applying.

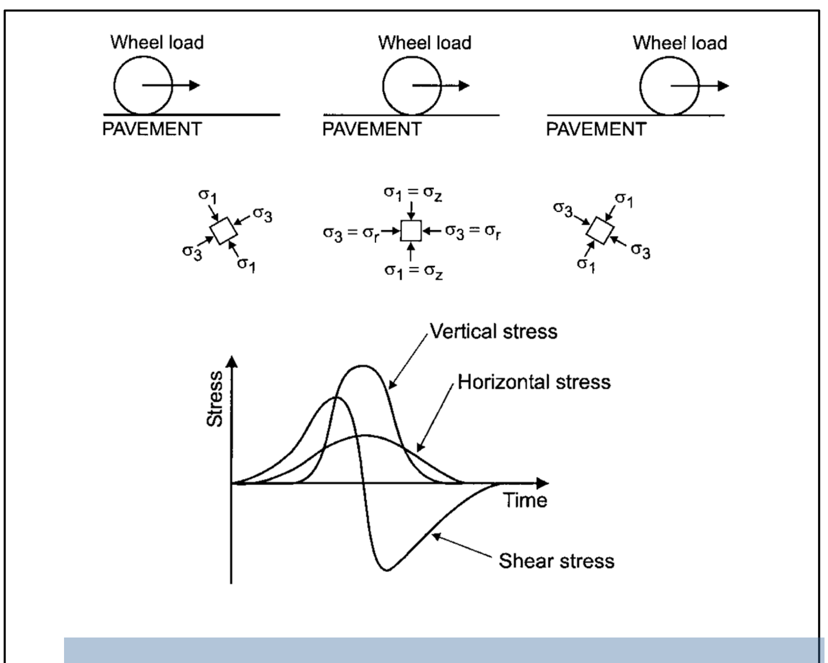

Figure 1-1 Stresses beneath the traffic load, taken from Lekarp et al. (2000a, p. 66)

In the context of stress analysis, unbound granular base spreads the load by its stiffness. Materials with less stiffness result in less spreading load and therefore higher stress acting on the subgrade. This phenomenon increases the possibility of a greater accumulation of plastic deformation in the subgrade and consequently greater rutting (Craciun, 2009).

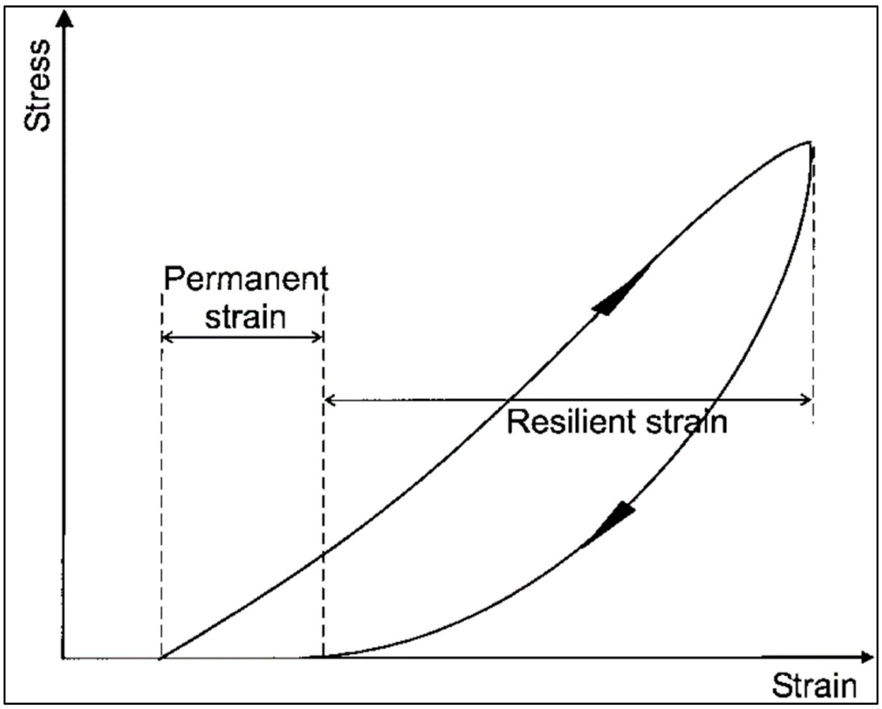

Figure 1-2 Strains in granular materials for one cycle of load, taken from Lekarp et al. (2000a, p. 66)

The permanent strain accumulated per load cycle is small in a well-designed pavement. But after subjecting to a large number of load repetitions, the permanent strain can become relatively large (Alexandria, 2013). The accumulation of permanent deformation in granular layers results in rutting of pavement surface (Alexandria, 2013). Repeated loading may cause excessive rutting due to excessive permanent deformation in the unbound granular layer. Furthermore, poor load spreading ability of unbound granular layers can result in plastic deformation in the subgrade due to higher stress acting on the subgrade as shown in Figure 1-

3 (Craciun, 2009). However, a pavement may lose its serviceability due to cracking in the surface layer caused by imposed deformation (Craciun, 2009).

The resilient modulus is defined as the ratio of the applied cyclic stress to the recoverable strain after many cycles of repeated loading (FHWA, 2006). It is well-known that granular pavement layers show a nonlinear and time-dependent elastoplastic response under traffic loading. To deal with this non-linearity and to differentiate from the traditional elasticity theories, the resilient response of granular materials is usually defined by resilient modulus and Poisson's ratio (Lekarp et al., 2000a).

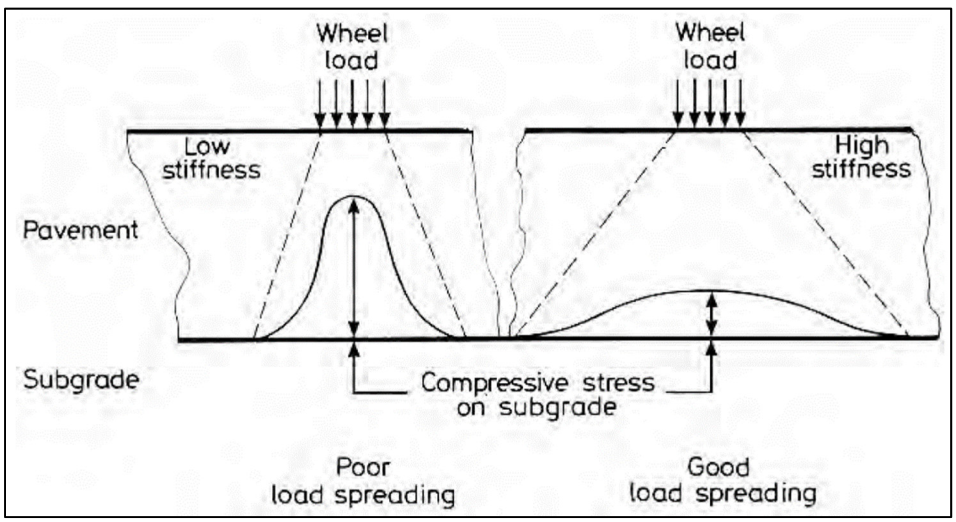

Figure 1-3 Concept of load spreading, taken from Craciun (2009, p. 8)

Lekarp et al., (2000 a, b) summarized the parameters that affect the resilient modulus and permanent deformation of granular materials. Among them, the level of applied stress and amount of moisture present in the material play an important role in the resilient modulus values. The resilient modulus increases with increasing confining pressure (Craciun, 2009). However, deviator stress has lower effects on resilient modulus compared to confining pressure (Lekarp et al., 2000a). The previous studies demonstrated the decrease of resilient modulus of aggregate with increasing saturation levels (Kolisoja et al., 2002).

Limitation of permanent deformation is one of the important criteria of pavement design. Generally, subjecting to repeated traffic loading the factors that increase the shear strength of aggregate lead into decreasing the permanent deformation (Alexandria, 2013). Among the various parameters affecting the permanent deformation of granular material, the importance of stress level and number of load repetitions are emphasized in the literature. It is accepted that the permanent deformation is related directly to deviatoric stress and intensely to confining pressure (Lekarp et al., 2000b). The permanent deformation increases by increasing the amount of repeated stresses (Alexandria, 2013).

Based on the literature review, since RG has negligible cohesion value and the sample fails within a few cycles of loading, the results of the permanent deformation and resilient modulus is not reported (Arulrajah et al., 2012).

1.5 Recycled glass blends

Since RG suffers from lack of cohesion resistance between particles (Wartman et al., 2004b), it cannot provide acceptable strength for using in some geotechnical engineering applications (Ooi et al., 2008). The idea of mixing RG with other materials arises from the fact that those materials enhance the shear strength behavior of RG (Disfani, 2011). However, some researchers applied RG to overcome the deficiencies of some materials like biosolids. The blends of glass with high friction properties and biosolids with high cohesion properties can produce appropriate strength for fill structure (Disfani, 2011). As another example, Grubb et al. (2006a,b) evaluated the blends of glass-dredged material in embankment and structure fill and demonstrated the geotechnical improvement in dredged material by addition of glass. It is accepted that both the main material and RG affects the geotechnical behavior of the blends. Various studies are available on the investigation of blending RG with the recycled materials, including recycled concrete, recycled asphalt, and waste rock, dredged material, soft clay etc. (Ali & Arulrajah, 2012; Arulrajah et al., 2014; Disfani et al., 2011a; Grubb et al., 2006a,b; Senadheera et al., 2005).

In Chapter 3 the state of the art of using RG in roadworks will be presented. This chapter, which was presented in Conference of the Transportation Association of Canada, covers the described literature review in the current chapter.

CHAPTER 2

APPROACH AND ORGANIZATION OF THE DOCUMENT

2.1 Research objectives

The main objective of this research is to study the effects of using recycled glass (RG) in granular materials of the pavement structure, namely base course on the hydraulic and mechanical properties of those layers. The specific objectives are:

(1) To evaluate and to compare the physical and hydraulic properties of RG and virgin aggregate considering different sizes.
(2) To assess the predictive methods of hydraulic conductivity of natural aggregate in order to suggest the fair prediction of hydraulic conductivity of RG.
(3) To investigate and compare the hydraulic and mechanical properties of blends of RG and base course aggregate considering different proportions of RG.
(4) To evaluate the resilient behavior of blends of RG and base course aggregate under cycling traffic loading.
(5) To suggest a model to predict the resilient modulus of granular base layer with RG based on CBR values.
(6) To create a model to predict the resilient modulus of granular base layer containing RG based on RG% and stress level.

2.2 Contribution

This research provides a contribution to sustainability in geotechnical engineering, particularly in road applications, environmental engineering, and economical aspects. The present research particularly contributes toward a better understanding of the hydraulic and mechanical characteristics of RG and granular aggregate and their blends in pavement structures. Some predictive models have been suggested based on the experimental results that contribute to the engineering applications of roadwork with RG. From environmental and economic aspects, using RG in roadwork can reduce the demand for landfill, thus leading to lower waste, lower energy usage, and gas emissions. This phenomenon leads to a more sustainable environment. Furthermore, using RG in roadwork contributes to conserving the natural aggregate sources and reduces the usage of them, which is again beneficial to environment and economy.

2.3 Novelty of research

While there are a number of studies available on geotechnical properties of RG, limited researches focus on base and subbase applications (Arulrajah et al., 2014; CWC, 1998; FHWA, 1998; Ooi et al., 2008), and only a small number of them have discussed the blends of RG with natural crushed rocks (CWC, 1998). Therefore, the current research aims to fill the gaps in knowledge of the behavior of RG blended with pavement base course aggregate, namely crushed limestone as a typical material in the province of Quebec. In the current study a new method of mixing is considered in which the aggregates will be replaced partially by the exact range sizes of glass by volume. Therefore, the size gradation of reference aggregate will not change. In this work some models are proposed to predict the mechanical properties of MG20, which is a size gradation envelope specified for the base course according to MTMDET, blends with RG. The suggested models for predicting M_r values based on %RG and stress levels and also for predicting M_r values based on CBR values can be used for engineering proposes. This study is one part of a greater project that aims to investigate using glass in Quebec roads as a solution of large amount of glass and also improve the behavior of pavement.

2.4 Methodology

This research program aims to investigate the effects of using RG on the performance of base course materials from hydraulic and mechanical aspects. To evaluate the behavior of RG and its blends with natural aggregates, an experimental plan is prepared and presented briefly in Figure 2-1. The experimental plan was separated into three phases.

In the first phase, the physical and hydraulic properties of pure RG and virgin aggregate were evaluated (Phase 1-1). Afterward the hydraulic properties of the blends of RG and crushed limestone as the natural aggregate were studied (Phase 1-2). In the second phase, the mechanical properties of the blends were investigated through a comprehensive laboratory test. In this step, five blends including different ratio of RG (0-100%) in fine fraction (0-5 mm) of MG20 size gradation envelope, which is specified for the base course according to MTMDET, were studied. In the phase three of this thesis, the author investigated the effect of using RG aggregate on the resilient performance of MG20 blends based on the resilient modulus test. In the end the results obtained from the experimental study through phase 1, 2, and 3 were analysed and some predicted models were suggested.

The efficiency of RG aggregate is evaluated through a comprehensive series of laboratory tests. The methods of laboratory tests are described in detail as the methodology part of related articles, which are presented in Chapter 4, 5, and 6 of this document. However, the summary of some undergone tests is presented in the current section through some Figures to give clear perceptions to the readers.

2.4.1 Hydraulic conductivity

The measurement of hydraulic conductivity of granular base course aggregate can be performed from in situ tests, laboratory tests, or estimated by the existing predictive models. In the laboratory, the hydraulic conductivity of granular soils is determined based on ASTM D2434 standard test method by a constant-head method for the laminar flow of water through granular soils (ASTM, 2006). This test is performed first by compacting a sample in a cylindrical permeameter to the maximum dry density level (Figure 2-2 (a)), and then saturation step is followed (Figure 2-2 (b)). Based on standard test method of ASTM D5101,

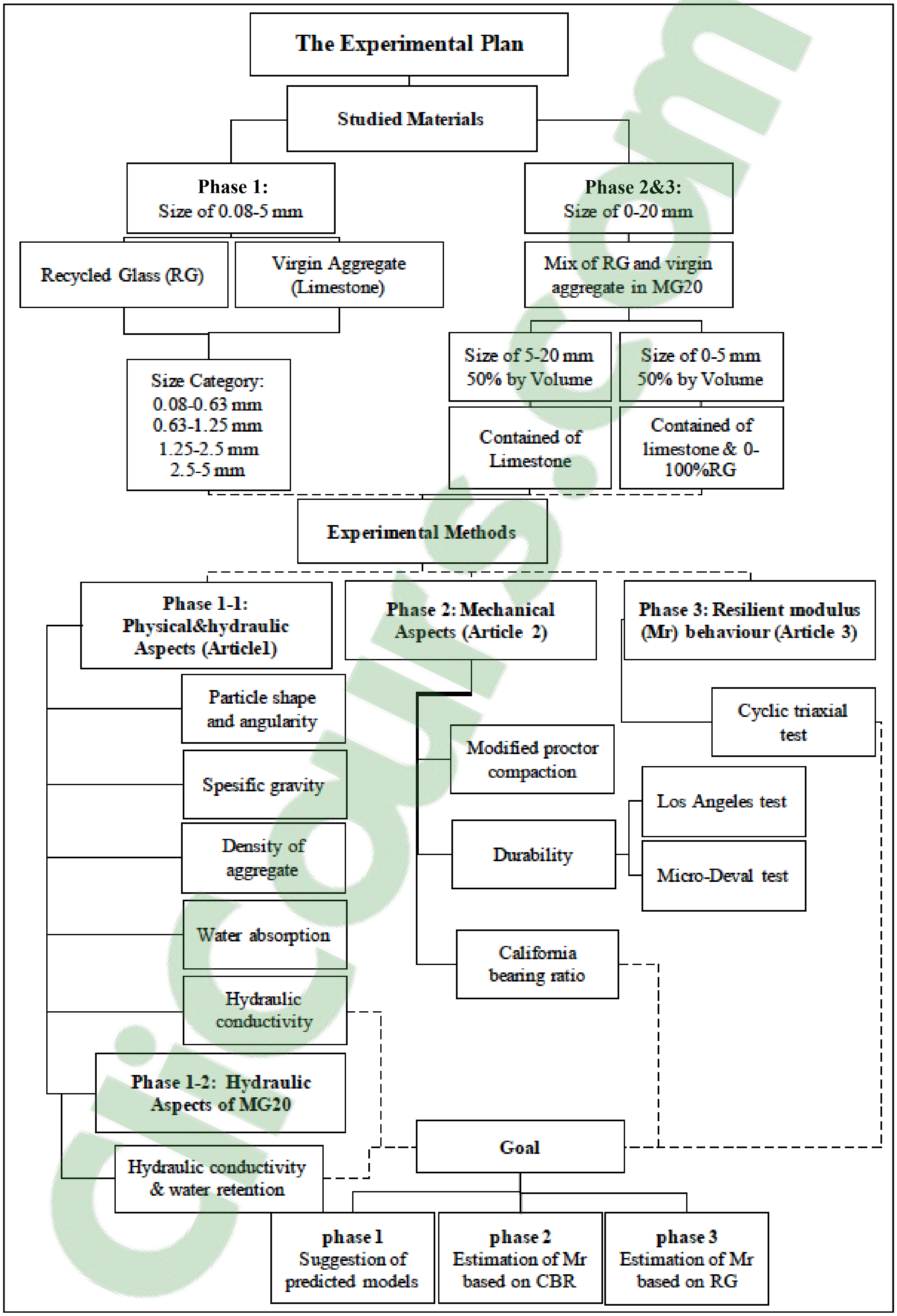

Figure 2-1 Framework of the methodology

oxygen and other gases in the permeameter and soil system are expelled by (1) attaching a carbon dioxide (CO2) line to the permeameter, and (2) regulating the gas flow at 2 L/min and purging the system for 15 min. After removing CO2, a slow saturation of specimens from bottom upward is followed (ASTM, 2012b).

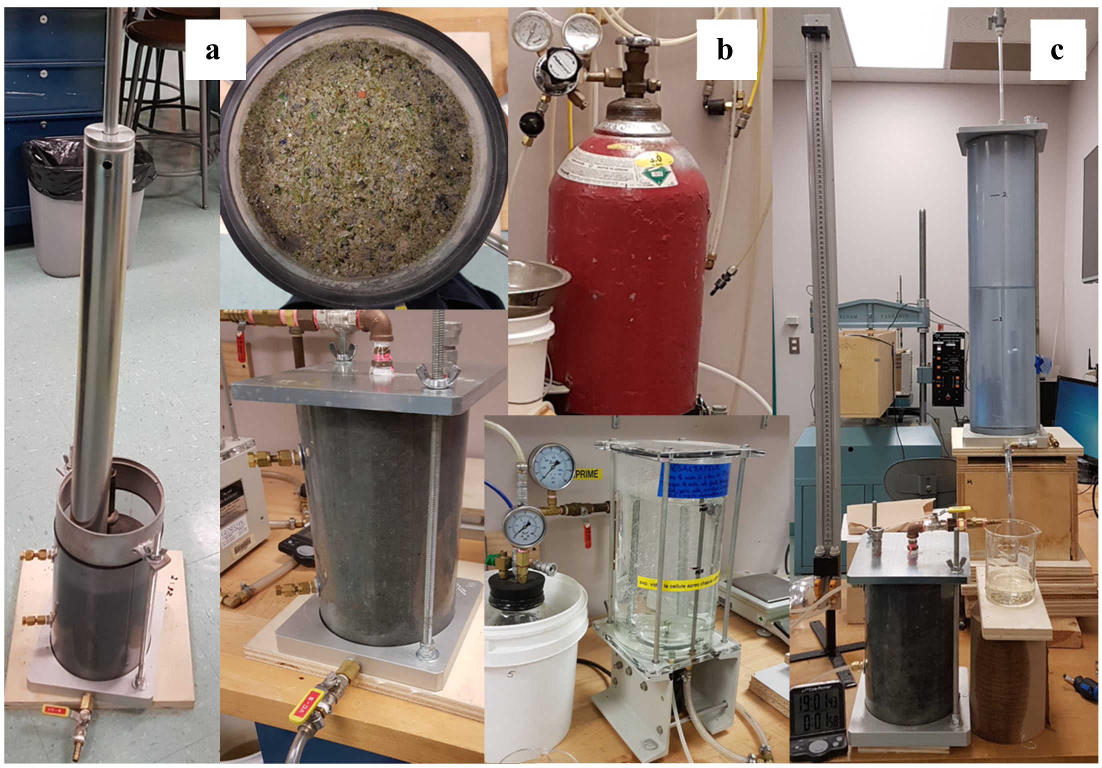

Figure 2-2 (a) Compaction step and prepared samples for saturation step (b) saturation of specimens from bottom upward with de-aired water after expelling the adhered oxygen by CO2 (c) hydraulic conductivity test based on constant-head method

2.4.2 Soil water characteristic curve (SWCC)

Measurement of the SWCC of granular base materials can be performed using the pressure plate apparatus (ASTM, 2008). The SWCC describes the change in water content in function of the change in matric suction and can be drawn from experimental data of water content corresponding matric suction (Rahardjo et al., 2010). Figure 2-3 shows the preparation steps of SWCC test including compaction and saturation, following the pressure plate test in the laboratory of soil mechanics at ÉTS. The principal restriction on the direct measurement of the SWCC of granular base course aggregate is the time-consuming laboratory test for the pressure plate apparatus. These difficulties are the possible reasons of lack for such data in the literature review for base course materials (Côté & Konrad, 2003).

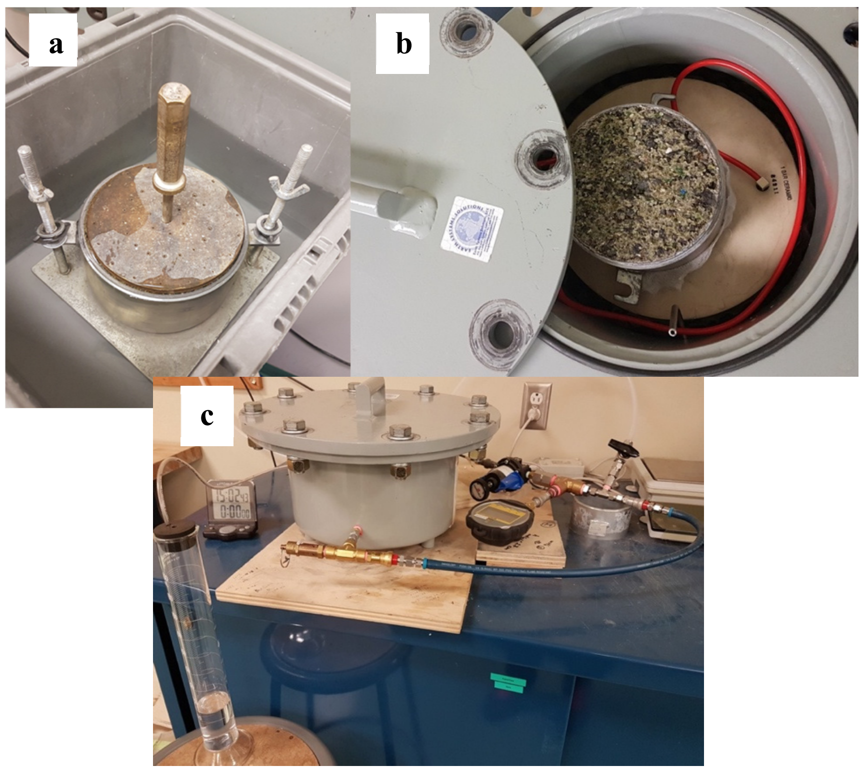

Figure 2-3 (a) Saturation step of compacted specimen (b) specimen on the saturated porous plate (c) SWCC test set-up

2.4.3 Modified Proctor compaction

Figure 2-4 presents the modified compaction equipment in the laboratory of soil mechanics at ÉTS. The laboratory compaction characteristics of studied materials is measured using modified Proctor test based on ASTM D1557 (ASTM, 2012a). The material at a selected molding water is placed in five layers into the Proctor mold with the diameter of 152 mm, with each layer compacted by 56 blows of 44.48 N rammer. The resulting dry unit weight is determined. The procedure is repeated for a sufficient number of molding water contents to establish a relationship known as the compaction curve. The values of optimum water content and modified maximum dry unit weight are determined from the compaction curve.

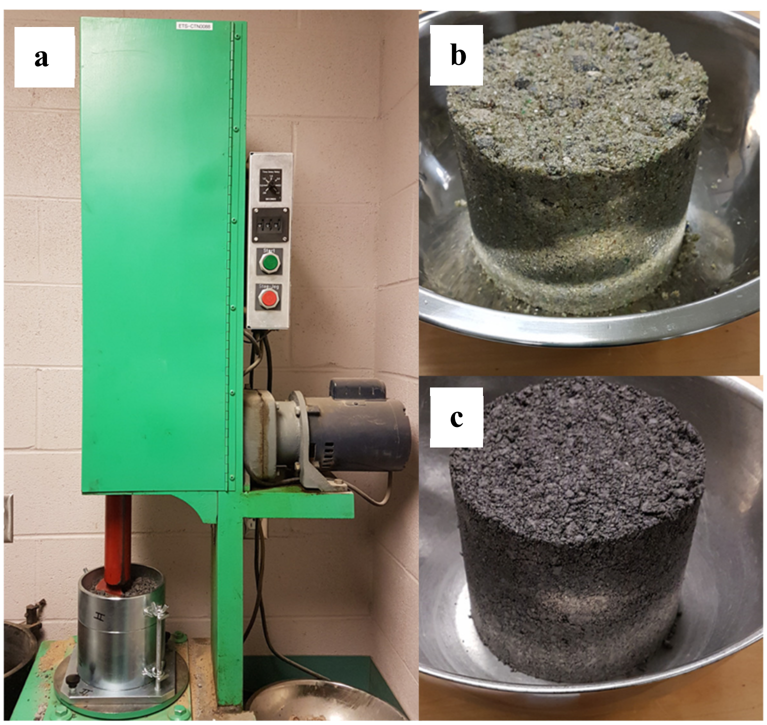

Figure 2-4 (a) Modified compact test with mechanical hammer (b) compacted sample of limestone blended with recycled glass aggregate (c) compacted sample of limestone aggregate

2.4.4 Los Angeles test

The Los Angeles (LA) test is a measure of degradation of mineral aggregate of standard grading resulting from a combination of actions, including abrasion or attrition, impact, and grinding in a rotating steel drum containing a specific number of steel spheres based on ASTM standard C131 (ASTM, 2014a). Figure 2-5 presents the LA abrasion test on RG in the laboratory of concrete at ÉTS.

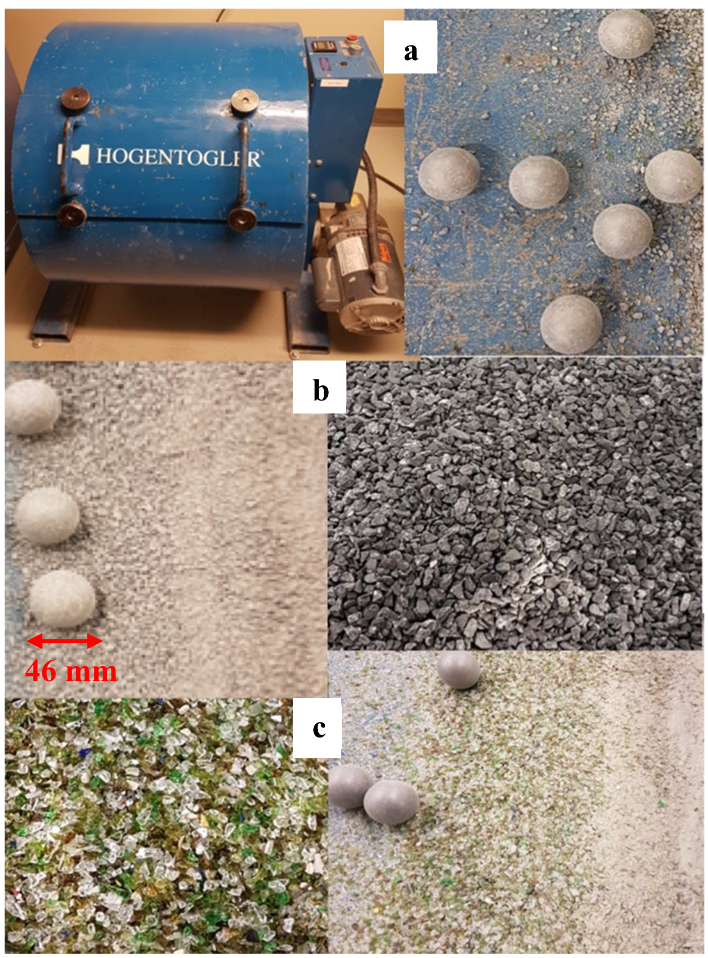

Figure 2-5 Los Angeles test machine

2.4.5 Micro Deval test

This test method covers a procedure for testing fine aggregate ($0.075\mu m$-4.75mm) for resistance to abrasion using the Micro-Deval apparatus based on ASTM D7428-15 (ASTM, 2015b). The Micro-Deval test is a measure of abrasion resistance and grinding with steel balls in presence of water. Figure 2-6 presents the Micro-Deval test on RG in the laboratory of concrete at ÉTS.

Figure 2-6 (a) Micro-Deval test machine (b) preparing sample for test (c) washing sample on the sieve No 1.18 mm after test to measure percent loss

2.4.6 California bearing ratio (CBR) test

CBR is determined in accordance with ASTM D1883 in which it is defined as "the ratio of the unit load on the piston required to penetrate 0.1 in. (2.5 mm) and 0.2 in (5 mm) of the studied material to the unit load required to penetrate a standard material of well-graded crusted stone" (ASTM, 2016a). Figure 2-7 shows the CBR test equipment in the laboratory of heavy structure at ÉTS.

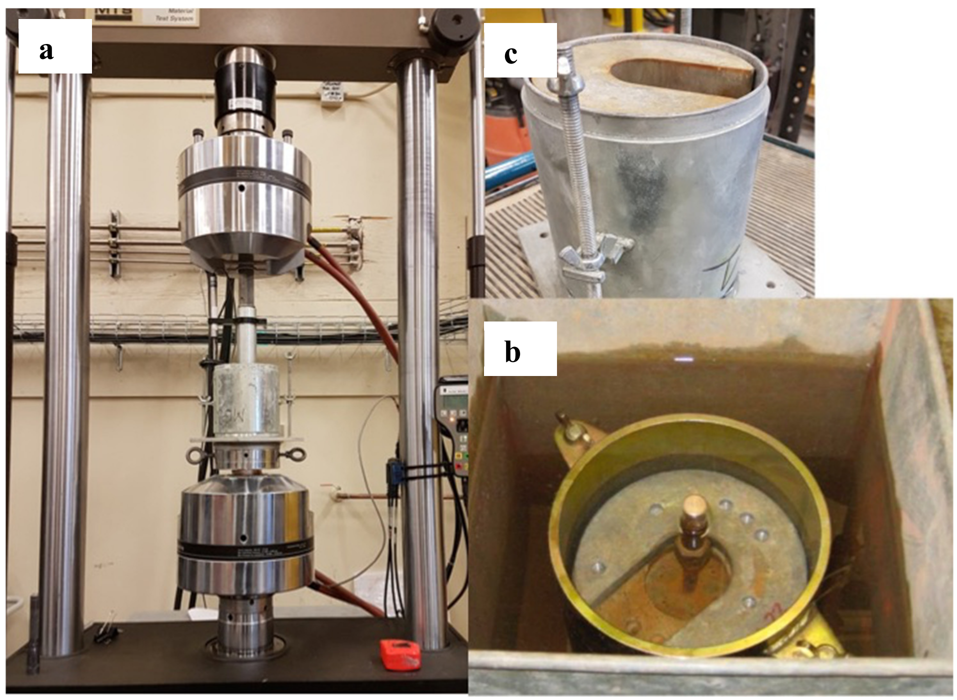

Figure 2-7 (a) CBR test machine (b) saturating the specimen (c) prepared specimen for CBR test

2.5 Organization of document

Introduction chapter started with an introduction about the problem statement and the necessity of research on using RG in pavement structure, general objectives of the dissertation, and the framework of the study.

Chapter 1 provided a critical review of existing literature and background related to using RG in roadwork applications.

Chapter 2 presents the objectives, the methodology and the organization of this thesis.

Chapter 3 presents a paper presented at the Conference of the Transportation Association of Canada (TAC) in title of "current state of art practice of use of glass in pavement structures". In this paper a comprehensive literature review on the distinct topics including state-of-the-art practice of use of RG in roadwork applications and performance of pavement structures with RG are presented.

Chapter 4 is in the form of a technical paper submitted to the Journal of Materials in Civil Engineering, entitled as "Physical and hydraulic properties of recycled glass as granular materials for pavement structure." In this study, which is described as phase 1 in the Figure 2-1, four size ranges of glass aggregate were considered, between 0.08 mm and 5 mm. The possibility of using RG as unbound aggregate in comparison with limestone aggregate as the reference aggregate was investigated. The experimental program included water absorption, specific gravity, compaction, coefficient of permeability, and water retention. First the physical and hydraulic properties of pure RG and virgin aggregate were evaluated (Phase 1-1 in Figure 2-1). Secondly, the coefficient of permeability and water retention of blends of RG and virgin aggregates in MG20 size gradation were investigated (Phase 1-2 in Figure 2-1). Finally, the predicted models of saturated hydraulic conductivity of natural aggregate were assessed based on the results of studied materials to suggest the fair estimation methods of hydraulic conductivity of RG aggregate.

Chapter 5 presents the second submitted article of this Ph. D program to the International Journal of Pavement Engineering (IJPE). The title of this article is “Feasible use of recycled glass aggregate in pavement unbound granular materials.” This paper, which follows the methodology described as phase 2 in Figure 2-1, covers the mechanical aspects of base course aggregate with RG. In this regard, six specimens in which RG replaced the same range size of the limestone aggregate in MG20 based on volumetric method, were considered and investigated. The RG and limestone aggregate were in the range size of 0-5 mm and 0-20 mm, respectively. The experimental studies included compaction, Los Angeles (LA) abrasion, Micro-Deval, and California bearing ratio (CBR) tests. Finally, a simple model was suggested for the RG blends to predict the resilient modulus values of studied materials based the CBR values.

Chapter 6 of this dissertation is in the form of a technical paper published in the Journal of Materials and Structures, entitled as “Resilient Modulus of Pavement Unbound Granular Materials Containing RG Aggregate.” The main goal of this investigation, which is shown as Phase 3 in Figure 2-1, was how the resilient modulus (M_r) of base course aggregate changes where MG20 undergoes different proportion of RG. In this regard, RG was replaced the same range size of the limestone aggregate in MG20. Five specimens were compacted to their maximum dry density and tested under cyclic triaxial loading. Eventually, based on the experimental observation a model was suggested to estimate the resilient modulus values of RG blends, which is one of the required inputs for flexible pavement design.

In the end a closing discussion on the objectives of this dissertation, the conclusion, some recommendations for future work, and a master reference list are presented.

CHAPTER 3

CURRENT STATE OF ART PRACTICE OF USE OF GLASS IN PAVEMENT STRUCTURES

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3.1 Abstract

The ever-increasing volume of waste materials, the shortage of landfill space and the limitation of natural resources motivate researchers to find innovative ways for recycling and reusing materials like waste glass. Using glass as an aggregate in the pavement structure is an innovative method of recycling and helps to reduce landfill. However, insufficient knowledge on mechanical and geotechnical characteristics of recycled glass as an aggregate and the shortage of information about the benefit of using it as the aggregate in unbound layers of pavement structures prevents its widespread use. This paper reviews the previous work on the usage of recycled glass as an aggregate in pavement structures. In this study, a critical review on the history and benefits of using recycled glass in pavement structures is presented, followed by a review of general studies on the use of recycled glass in pavement structures in order to improve the properties of pavement. Also, different properties of recycled glass are compared based on past research. Studies indicate that engineering properties of recycled glass are generally equal to or better than those of most natural

aggregates. Glass particles characteristics suggest that glass can be used for many applications including base course, subbase, embankment, etc.

3.2 Introduction

Waste materials are related to any material with no enduring value which is produced by human and industrial activities (Serpell and Alarcon, 1998). In the year of 2012, 1,095,000 tons of residual waste materials were recovered for different waste sorting centers of Quebec, an increase of 5% in comparison with the year of 2010 (RECYC-QUÉBEC, 2012). It is also worth to note that the waste sorting centers of Quebec sent 970,000 tons of materials to recyclers and packers for recycling and around 7% of that is glass (RECYC-QUÉBEC, 2012). Closed loop recycling seems to be the best environment-friendly method in which post-consumer waste is collected, recycled and used to make new products. However, using closed loop recycling is not practical in the production of some new materials considering the standards applied on the quality of raw materials like in the case of manufacturing glass. So, the amount of waste glass due to mentioned manufacturing criteria has increased (Taha and Nounu, 2008). Furthermore, high-priced and complicated processes for separating high quality waste materials with the convenient specifications is considered another obstacle in using waste material in closed loop recycling (Disfani, 2011). The large volume of required natural resources and the ever-increasing demand of landfill space for waste materials put pressure on recycling more waste materials (Halstead, 1993). Therefore, finding alternative methods to use tons of waste materials seems to be a worldwide concern (Taha and Nounu, 2008). In this regard three important areas need to be considered about waste recycled materials, including economy, compatibility with other materials and also recycled materials properties as they should satisfy the minimum criteria of each application (Tam and Tam, 2006). One of the most attractive methods among innovative ways of reusing waste materials is using them in civil engineering applications (Strenk et al., 2007).

Glass is a material that can be recycled many times without changing its chemical properties. For instance, glass bottles can be crushed into cullet and melted for producing new bottles without changing its properties. Recycled glass separated by colour (green, clear and amber) can be used for manufacturing. But mixed-colour glass, which is unsuitable for use as containers, is used for other applications including road application, concrete aggregate and fiber glass insulation or sent to landfill (Shayan and Xu, 2004). Recycled glass can be used as alternative aggregate in both concrete and asphalt and as unbound aggregate replacement for pavement subbase and base layers. When recycled glass is used as bound material in concrete or asphalt is named glascrete and glasphalt, respectively (Landris and Lee, 2007).

In this paper, we review the use of recycled glass as an unbound aggregate in pavement structure and we compare different result based on past research. This is done to motivate designers to use glass as an aggregate in roadwork.

3.3 Recycled glass in road work

Using recycled glass in civil engineering projects is good both for environmental reasons and economic reasons. Environmental benefits include conservation of landfill space, conservation of natural aggregate resources and saving energy. Energy is saved by eliminating or reducing haul distance of recycled glass to the landfill and new aggregate from the quarry as well as energy required to melt glass for the container industry. Using recycled glass in civil engineering projects leads to less transportation and material cost compared with virgin aggregate and reduced haulage suggests reduced traffic and less wear and tear on haul routes (Ooi et al., 2008).

In 1995, the Technical University of Texas conducted a study on the use of waste glass as a building material in road structures. This project was conducted jointly by the Federal Department of Transport and the committee on the preservation of natural resources of Texas. Both organizations wanted to set up some projects in which the potential use of glass could be tested, and also could reduce the solid waste in the municipality. The results showed that using waste glass did not cause any particular problem, both for the producer and the contractor. Thus, the glass particles can be blended with aggregate perfectly and behave as a normal material (Lupien, 2006). Several research projects have been aimed at using recycled glass in pavement construction. In some of them, glass was substituted for a portion of conventional aggregate and in others, 100% of glass was used in some parts of pavement structures (Lupien, 2006). Although crushed glass is observed to be good for drainage and to have acceptable strength, shortage of knowledge relating to engineering properties prevents recycled glass to be used to its full potential (Wartman et al., 2004b).

The properties of recycled glass that is crushed and screened to pass 9.5 mm sieve is similar to natural aggregate and can be used as an unbound aggregate mixed with other aggregates in pavements' base and subbase (Landris and Lee, 2007). Based on the study on the potential of using recycled glass with different particle size in road work, different recycled glass types were considered: Fine Recycled Glass (FRG), Medium Recycled Glass (MRG) and Coarse Recycled Glass (CRG) with maximum particle size of 4.75, 9.5 and 19mm respectively. The smaller size of crushed glass particles is more similar to the natural aggregate shape (Disfani et al., 2011b). Mixed-color glass, which has little or no commercial recycling value, has good potential for use in highway construction. It has been successfully utilized as granular base or fills for many years in Wisconsin as well as trench backfill and embankments (WTIC, 1999). Different type of debris, mainly paper, plastic, metals, organic contaminants, etc., exists in recycled glass which should be restricted to a minimum. The geotechnical parameters of recycled glass as an aggregate depend on the glass percentage, glass gradation, compaction effort and, to a minor level, on the glass source and debris content (CWC, 1998).

A thorough laboratory evaluation of geotechnical and geoenvironmental behaviors has been conducted in Australia to study the sustainability of using recycled glass-biosolids blends in road applications. As an innovative idea, weaknesses of recycled glass and biosolids when used alone can be removed by mixing them and also their strength properties can be increased (Disfani, 2011).

Table 3-1 shows some specifications published on qualifications required for using recycled glass in some roadwork. As can be seen, Federal Highway Administration (FHWA) proposes using maximum percentages of 15% and 30% of recycled glass by weight in base and subbase courses, respectively (FHWA, 1998). Also, crushed glass (CG) between 20% and 80% by weight blended with dredged materials (DM) can offer the designer a flexibility to improve several design parameters (Grubb et al., 2006b).

Table 3-1 Some road application of recycled glass

Recommended applications	**Optimum limit of recycled glass**	**Blended material with recycled glass**	**Recommendations**	**Reference**
Base layer	15%	Natural aggregates	Gradation specification, max debris level 5%	(FHWA, 1998)
Subbase layer	30%			
Base	15%	Natural aggregates	max debris level 5%	(CWC, 1998)
Subbase	30%			
Embankment	30%			
Base	10% - 20%	Natural aggregates	max debris level 5%	(MPSC, 2000)
Structural fill, backfill and embankment	50%	Marginal materials	-	(Wartman et al., 2004a)
Fills	20%-80%	Dredged material	-	(Grubb et al., 2006b)
Base	20%	Natural aggregates	a maximum size of 12.7 mm for recycled glass; relatively free from debris	(Finkle et al., 2007)
Subbase	30%	Crushed rock	Being careful about debris content	(Ali et al., 2011)
Subbase	30%	Crushed concrete	-	(Ali & Arulrajah, 2012)

3.4 Performance of pavement structures with recycled glass

For each application of recycled glass particular engineering properties are important and need to be fulfilled. For instance, for base and subbase applications the important material and engineering properties include specific gravity, gradation, workability, durability, compaction, permeability and shear strength (CWC, 1998).

Physically, crushed glass particles have angular shape and include some flat and elongated particles. The degree of processing (for instance crushing) is an important aspect which affects the degree of angularity and the quantity of flat or elongated particles. The smaller the particles, due to extra crushing, the less angularity and the fewer flat and elongated particles (FHWA, 1998). Different suppliers of recycled glass produce different particle size distribution and debris levels based on different machines or processes in crushing waste glass which results in different geotechnical properties of recycled glass (Disfani et al., 2011b). So, different researchers obtain different results of geotechnical parameter tests on recycled glass. Comparison between the results of tests conducted on recycled glass and natural aggregates provide a good basis to understand the behavior of recycled glass (Disfani et al., 2011a).

Table 3-2 presents the basic physical properties of recycled glass particles based on another researcher works. As can be seen the proportion of fine particles is gradually low and most of the particles are within sand or gravel sizes. So, most recycled glass is principally classified as well graded sand or well graded gravel materials. Also based on past research, the specific gravity of recycled glass is typically 2.41-2.54 while typical values for most soils range from 2.65 to 2.72 (FHWA, 2006).

Based on studies conducted by some research teams, recycled glass particles have a lack of cohesion which affects shear strength (Disfani et al., 2011b; Ooi et al., 2008; Wartman et al., 2004b). Some research teams offered blending recycled glass particles with other materials like crushed rock, dredged materials, etc. to enhance several design characteristics of recycled glass (Grubb et al., 2006b). Properties and proportions of both the main soil and the recycled glass component affect the behavior of the mixture (Disfani, 2011).

Table 3-2 Basic physical properties of recycled glass particles

Reference	**USCS Soil classification**	**Maximum particle size (DeLong et al.)**	**Coefficient of uniformity (C_u)**	**Coefficient of curvature (C_c)**	**Fine content (≤0.075mm) %**	**Sand content (0.075mm-4.75mm) %**	**Gravel content (≥4.75mm) %**	**Specific gravity (G_s)**
(FHWA, 1998)	SP	25.4	4.5	1.7	0.6	63	36.4	1.96-2.41
(CWC, 1998)	SW	19.2	9.8	1.5	2	70	28	2.49
(Su & Chen, 2002)	SP	4.75	4.4	1.2	1	99	0	2.54
(Wartman et al., 2004a)	SW	9.5	6.2-7.2	1.1-1.3	1.2-3.2	70-91.3	5.5-28.8	2.48-2.49
(Grubb et al., 2006b)	SP	9.5	4.5	1.2	0.4	70.4	29.2	2.48
(Ooi et al., 2008)	SP-SM	9.5	13	0.8	6	91	3	2.5
(Ali & Arulrajah, 2012)	SW	5	6.2	1.5	2.8	71.2	26	2.49
(Disfani et al., 2012)	SW-SM	4.75	7.6	1.3	5.4	90	10	2.48
(Disfani et al., 2012)	SW-SM	9.5	16.3	2.2	5.2	48	52	2.5

SP= Poorly graded sand based on Unified Soil Classification System (USCS)

SW= Well-graded sand based on USCS

SM= Silty sand based on USCS

FHWA recommends that recycled glass usage in granular base course should be restricted to the replacement of fine aggregate sizes considering that fine glass includes durable particles similar to sand. Table 3-3 presents gradations of recycled glass particles recommended by FHWA in which glass particles behave as a very stable fine aggregate (FHWA, 1998). In the following sections, a summary of typical mechanical, hydraulic and thermal properties of recycled glass are presented.

Table 3-3 Recommended glass gradation for use as a granular base material
Taken from FHWA (1998, pp. 20-21)

Size	% Finer
6.35 mm (1/4 in)	10 - 100
1.68 mm (No. 10)	0 - 50
0.42 mm (No. 40)	0-25
0.075 mm (No. 200)	0-5

3.4.1 Compaction Test

In civil engineering practice, in-situ soils do not often satisfy the standards of construction as they may be weak, highly compressible, or have a higher hydraulic conductivity than acceptable (Holtz et al., 2011). One possibility to address this problem is to stabilize or boost the engineering properties of the soils. Compaction is a mechanical approach to stabilize soil. Compaction contributes to densify soil and rock by applying mechanical energy involving a modification of the water content as well as the gradation of the soil (Holtz et al., 2011).

As a comparison, the results of compaction tests confirmed that the moisture-density curve for recycled glass has a convex shape, similar to those of natural aggregates. The difference between them is based on the fact that the recycled glass moisture-density curve has a flatter shape than natural aggregate, indicating the relative insensitivity of recycled glass compaction to moisture content. So, recycled glass shows stable compaction behavior and decent workability in a large range of water content (Wartman et al., 2004b). Results of standard and modified compaction tests conducted by different research teams are presented in Table 3-4. As indicated in Table 3-4, typical modified compaction densities of recycled glass are between 18-19 kN/m3 with optimum water contents (W_{OPT}) of 5.7-7.5% based on FHWA (FHWA, 1998). The maximum dry density (γ_{dMAX}) for different recycled glass source shows little difference due to different particle size distributions of recycled glass sources.

Similar to natural aggregates, the modified Proctor values show higher γ_{dMAX} than those of the standard compaction values (Wartman et al., 2004b).

It can be seen that the maximum dry density of soil-glass blends depends on the kind of blended material and consequently the distribution of particles in blends. Grubb et al. (2006b) studied moisture-density relationships of crushed glass (CG)/dredged material (DM) blends. Increasing CG content resulted in decreasing optimum moisture content and increasing γ_{dMAX}. From Table 3-4, it is evident that the values of γ_{dMAX} usually stay within the limits of 100% CG and 0% CG (100% DM) (Grubb et al., 2006b). In an opposite trend, when CG is blended with kaolinite and quarry fines, Wartman et al. (2004a) indicated that blends of CG with fine-grained soils (kaolinite (K) and quarry fines (QF)) are denser than the individual materials because of better packing of the blends. So, it seems that DM prohibits tight packing to unit weights higher than the raw materials, as can be observed for blends of CG with K and QF (Grubb et al., 2006b). In blends of CG with K and QF, maximum dry density of the blends generally increases with soil content for low soil content blends as a result of: (1) a shift in increasing net specific gravity (G_s=2.48 for glass versus G_s=2.7 for soil) and, (2) becoming more well graded of soil-glass blends. But maximum dry density of the blends decreases with soil content at higher soil proportion considering that for the same specific gravity, γ_{dMAX} of well graded soils is usually more than poorly-graded soils. At the higher soil proportions, the γ_{dMAX} decreases due to the blends becoming more poorly graded (Wartman et al., 2004a).

Table 3-4 Typical mechanical properties of recycled glass and its blends with other materials

Reference	**RG, %**	**Blended material**	**Standard γ_{dMAX}, KN/m3**	**W_{OPT}, %**	**Modified γ_{dMAX}, KN/m^3**	**W_{OPT}, %**	**CBR, %**	**LA, %**
(FHWA, 1998)	100	natural aggregates	-	-	18-19	5.7-7.5	-	30-42
	50		-	-	-	-	42-125	-
	15		-	-	-	-	132	-
(CWC, 1998)	100	-	-	-	-	-	-	29.9-41.7
	50		-	-	-	-	30-60	-
	15		-	-	-	-	132	-
(Wartman et al., 2004b)	100	Kaolinite	16.8	12.8	18.3	9.7	-	24
	90		-	-	20.7	6.8	-	-
	80		-	-	20.5	6.8	-	-
	50		-	-	18.5	10	-	-
	0		-	-	16	16	-	-
(Wartman et al., 2004b)	90	Quarry fines	-	-	20.7	8	-	-
	80		-	-	20.5	8	-	-
	50		-	-	20	9	-	-
	0		-	-	19	10.8	-	-
(Grubb et al., 2006b)	100	Dredged material	17.1	8	18.7	8	-	-
	50		14.8	24	16.6	15	-	-
	40		13.7	25	16.1	11.5	-	-
	20		11.8	29	15.1	11	-	-
	0		10.8	39	12.2	29	-	-
(Ooi et al., 2008)	100	FRG	-	-	18.5	9.7	75-80	27
		MRG						33
(Arulrajah et al., 2014)	100	Waste rock (WR)	-	-	18.4	9.2	44	27
	50		-	-	21.3	8.81	121	25
	30		-	-	21.8	9.31	152	24
	20		-	-	22.1	9.14	165	24
	15		-	-	22.4	8.54	199	23
	0		-	-	23	8.67	181	24
(Arulrajah et al., 2014)	50	RCA	-	-	19	11.92	98	30
	30		-	-	19.5	9.41	120	30
	20		-	-	19.8	11.54	144	31
	15		-	-	19.7	12.23	176	32
	0		-	-	19.7	13.8	211	28
(Disfani et al., 2011a)	100	FRG	16.7	12.5	17.5	10	42-46	24.8
(Disfani et al., 2011a)	100	MRG	18	9	19.5	8.8	73-76	25.4

Based on the studies by Arulrajah et al. (2014), for fine glass (FRG)-waste rock (WR) blends and fine recycled glass-recycled concrete aggregate (RCA) blends, with the maximum particle size of 4.75 for glass and 20 mm for RCA and WR, WR had the maximum dry density, 23 kN/m3, and fine recycled glass had the lowest of 18.4 kN/m3. Higher specific gravity and higher coefficient of uniformity C_u of RCA and WR are two important parameters which contribute to higher density of blends. Increasing C_u value results in higher variations in particle sizes. Consequently, smaller particles will fill pore spaces among larger particles and results in denser materials with higher dry density (Arulrajah et al., 2014).

3.4.2 California Bearing Ratio Test

California Bearing Ratio (CBR) test measures soil strength indirectly based on "resistance to penetration by a standardized piston moving at a standardized rate for a prescribed penetration distance" considering moisture content and compaction level (FHWA, 2006). A minimum CBR of 100% and 80% are recommended by National Cooperative Highway Research Program (NCHRP, 2003) qualifications for base course and subbase material for a light duty haul road respectively. The CBR values of recycled glass based on different researchers are presented in Table 3.4. Disfani et al. (2011b) conducted CBR tests on fine recycled glass (FRG) and medium recycled glass (MRG) samples considering both standard and modified compaction parameters. Results proved that MRG samples shows higher CBR values than FRG samples as a result of higher maximum dry density of the MRG samples in compaction tests. In MRG samples better compaction due to higher maximum dry density results in better contact of particles which leads to better shear behavior. Also, the CBR values of recycled glass obtained by Ooi et al. (2008), 75%-80%, are comparable to those of measured by Disfani et al. (2011b) for FRG samples prepared by modified compaction.

Based on studies conducted by Clean Washington Centre (CWC) (1998), the CBR values of a blend with 15% glass was higher than those measured for samples with 50% glass regardless of the size of glass particles. Also, the CBR values of blends with 15% glass were similar to those of the crushed rock samples which are typically in the range of 40 to 80, regardless of the compaction method for preparing samples (CWC, 1998). However, by increasing the content of recycled glass to 50%, a reduction of CBR value was occurring considering compaction methods (CWC, 1998). The CBR values of recycled glass blends with natural aggregates based on FHWA follows the same trend, by increasing glass contents CBR values decrease (FHWA, 1998). The results of studies done by Disfani et al. (2011b) indicated that most of the blends of fine recycled glass-recycled concrete aggregate (FRG/RCA) and fine recycled glass-waste rock (FRG/WR) fulfilled the requirements for use in pavement base layers except the FRG50/RCA50 with CBR of 98% that is less than the acceptable value. Also, the CBR values for FRG seem to be the lowest due to its lower strength and quality than WR and RCA aggregates, and higher in the blends with less glass percentages (Disfani et al., 2011b).

3.4.3 Los Angeles test

The Los Angeles (LA) test is a common test in highway and material engineering for evaluating the resistance of aggregates to abrasion, impact and grinding (Wartman et al., 2004b). The LA test is a measure for degradation of mineral aggregates of standard grading resulting from "a combination of actions including abrasion or attrition, impact, and grinding in a rotating steel drum containing a specified number of steel spheres" (ASTM, 2014a). The results of LA abrasion tests show that the soundness of recycled glass is not as good as that of natural crushed rock, with losses at least two times greater than that of crushed rock. It is notable that the durability of crushed rock is dependent on the kind of crushed rock (Landris et Lee, 2007).

The LA abrasion values of recycled glass and its blends with other materials based on different researchers are presented in Table 3-4. As can be seen, all values are below the maximum allowable value of 45% permitted by AASHTO T 96 for the aggregate used for base course (FHWA, 2006). FRG has a lower LA abrasion value of 27% than MRG with a value of 33% which indicates that larger glass particles abrade more (Ooi et al., 2008). The studies carried out by Arulrajah et al. (2014) showed that FRG and RCA had similar durability whereas WR had the smallest LA value and was considered the most durable aggregate.

3.4.4 Shear strength parameters

The most typical tests to evaluate the shear strength parameters of aggregates are direct shear test, triaxial shear test, and resilient modulus test (Landris and Lee, 2007). In the direct shear test, failure occurs in a predetermined shear plane, not in the weakest plane, and because of great stress concentration at the boundary of the specimen, a highly non-uniform stress is obtained through the test specimen. However, this method is a quite simple and perhaps the oldest test for soils in which a shear box separated horizontally is used to identify the shear strength (Holtz et al., 2011). The triaxial shear test, which allows three-dimensional loading of the sample, is capable of modelling in-situ loading conditions (CWC, 1998). There are three different testing scenarios based on the drainage path before and during the shear test including Unconsolidated-Undrained (Kolisoja et al., 2002), Consolidated-Undrained (CU) and Consolidated-Drained (CD) (Holtz et al., 2011). The CD method is suggested for evaluation of shear strength properties of recycled glass based on its good drainage characteristics (Disfani et al., 2011b).

The results of some studies on shear strength parameters of recycled glass and its blends with other materials based on direct shear tests are presented in Table 3-5. Clean Washington Centre (CWC, 1998) reported the values of the drained internal friction angle of recycled glass samples which are close to the values achieved by Disfani et al. (2011b), while the values found by Wartman et al. (2004b) are a bit higher. The results of the mentioned studies proved that the friction angle of the recycled glass samples is comparable to those of dense and coarse natural aggregates (CWC, 1998; Disfani et al., 2011b; Lambe & Whitman, 1969; Wartman et al., 2004b). Normally, for evaluating the results of direct shear test on pure recycled glass, cohesion is considered to be zero (Wartman et al., 2004b).

Table 3-5 Shear strength parameters of recycled glass and its blends with other materials

Reference			Direct shear test			Triaxial shear test	
	Percentage of recycled glass	Blended material	Normal stress (KPa)	Drained internal friction Angle (degree)	Drained Cohesion (KPa)	Drained internal friction angle (degree)	Drained Cohesion (KPa)
(FHWA, 1998)	100	-	-	51-53	0	-	-
(CWC, 1998)	100	-	49-98-196	49-53	0	42-46	-
(Grubb et al., 2006b)	100	-	45-160	42	0	-	-
	50	dredged material		32	26	-	-
	40			31	25	-	-
	20			33	26	-	-
	0			33	20	-	-
(Wartman et al., 2004a)	80	Kaolinite	30-190	38	20	-	-
	50			35	27	-	-
	0			25	47	-	-
(Wartman et al., 2004a)	80	Quarry fines	30-190	47	15	-	-
	50			40	27	-	-
	0			39	25	-	-
(Wartman et al., 2004a)	100	-	0-60	59-63	0	48-48	0
			60-120	55-61	0		
			120-200	47-68	0		
(Ooi et al., 2008)	100	-	46.1-262	41	0	-	-
(Disfani et al., 2011a)	FRG	-	30-120	45-47	0	40	0
			60-240	42-43	0	38	0
			120-480	40-41	0	35	0
(Disfani et al., 2011a)	MRG	-	30-120	52-53	0	42	0
			60-240	50-51	0	41	0
			120-480	-	0	41	0
(Arulrajah et al., 2014)	100	WR	-	-	-	38	0
	50		-	-	-	47	31
	30		-	-	-	47	43
	20		-	-	-	49	43
	0		-	-	-	48	70
(Arulrajah et al., 2014)	50	RCA	-	-	-	45	33
	30		-	-	-	46	63
	20		-	-	-	45	53
	0		-	-	-	51	76

From Table 3-5 it can be seen that the values of internal friction angle obtained from triaxial tests are less than those measured by the direct shear test for equal confining stresses because of different boundary conditions between the two tests. Also, the values of internal friction angles decrease with increasing the normal stress level based on direct shear test (CWC, 1998; Disfani et al., 2011b; Wartman et al., 2004b). As a comparison between fine recycled glass (FRG) and medium recycled glass (MRG) samples, the friction angle of MRG is higher than those of FRG, in accordance with higher CBR values of MRG specimen. This trend can be attributed to better contact of particles in compacted MRG samples (Disfani et al., 2011b).

The results of CD triaxial tests on recycled glass blends with WR and RCA proved that both cohesion and friction angle increase with increasing portions of RCA and WR (Arulrajah et al., 2014). The shear strength of these recycled materials, RCA and WR, are in agreement with coarse natural aggregates. But, cohesion of FRG was 0 KPa and it had the lowest friction angle as the characteristics of FRG are comparable to coarse sand with negligible cohesion (Arulrajah et al., 2014). The results of studies conducted by Grubb et al. (2006b) indicated that by increasing glass content, friction angle and cohesion of the mixture increases and decreases, respectively. Also, by addition as little as 20% of crushed glass, the workability and construction characteristics of dredged material are enhanced by improvement of the physical properties of dredged materials including reduction in moisture content, plasticity index and coarsening of the grain size distribution (Grubb et al., 2006b). Wartman et al. (2004a) conducted research to investigate the possibility of using recycled glass to enhance the engineering behavior of fine-grained, marginal materials (kaolin, quarry fines). The results indicated that generally by adding recycled glass to fine-grained soils, the cohesion decreased while the frictional strength increases. Therefore, recycled glass can enhance the frictional properties of fine-grained soils and conversely fine-grained soils can improve cohesion properties of recycled glass (Wartman et al., 2004a).

3.4.5 Resilient modulus

Resilient modulus is a key property of soils and unbound pavement materials which is widely accepted for computing the mechanical response of pavement materials subjected to loading (Doré and Zubeck, 2009). The resilient modulus is determined in a cyclic triaxial test and indicates the stiffness of aggregates after repeated load-unload cycles (CWC, 1998). While static load testing of granular materials is not capable of modeling the repetitive loading of vehicles that occurs in pavement, the resilient modulus is a property that simulates the behavior of pavement materials under repetitive loading. The important factors influencing the resilient modulus include aggregate mineralogy, particle characteristics, density, moisture content and particle size distribution (Senadheera et al., 2005). Results of studies conducted by CWC (1998) on 15% and 50% recycled glass blends with crushed rock showed that adding recycled glass particles decreases the resilient modulus and increasing glass content leads to further reduction. Also, it was noticeable that recycled glass content as high as 50% showed a resilient modulus value convenient for use in pavement design (CWC, 1998). Senadheera et al. (2005) studied the resilient modulus of recycled glass blends with caliche, which is a conventional granular material for the use in subbase layers. The results from resilient modulus tests indicated that addition of glass up to 30% to a relatively weaker material like caliche, increases the strength of blends (Senadheera et al., 2005).

Using repeated load triaxial tests for determining the resilient modulus of pure FRG and MRG samples was not possible as test specimens failed either prior to starting the test or after only a few applied load cycles due to the lack of cohesion among glass particles. Resilient modulus of FRG blends, which was limited to 30% of FRG, with WR and RCA was studied by Arulrajah et al. (2014) and FRG content was limited to 30%. The results of repeated load tests on FRG/RCA indicated that resilient modulus was sensitive to both of moisture content and FRG content. Results of studies conducted by Arulrajah et al. (2014) indicated that the resilient modulus for fine recycled glass and recycled concrete aggregate (FRG/RCA) blends is sensitive to FRG content, and a higher content of glass could potentially produce lower resilient modulus, most probably because of the reduction of active cement content in the blends. The results of this study indicated that the performance of FRG/RCA blends in terms of the resilient modulus was better than those of natural granular subbases. Although, resilient modulus for recycled glass and waste rock (FRG/WR) blends, was not sensitive to changes in FRG content. The behavior of FRG/WR blends in aspect of the resilient modulus was comparable with those of natural granular subbase (Arulrajah et al., 2014).

3.4.6 Hydraulic Conductivity of Recycled Glass

In addition to the mechanical properties, drainage properties of aggregates are important parameters in pavement design. Granular layers in pavement structures play 2 fundamental roles; (1) act as a foundation to provide mechanical support to its upper layer and (2) supply sufficient drainage to conduct permeated water out of pavement structure (Haider et al., 2014). The important factors affecting permeability of materials include particle size distribution, particle shape and texture, void ratio, etc. (Head, 1994).

The results of hydraulic conductivity test of recycled glass particles and its blends with other materials based on previous studies are presented in Figure 3-1(a) and (b) respectively. Figure 3-1(a) reports hydraulic conductivity values between 0.000161 and 0.26 cm/s for 100% of pure recycled glass particles. From Figure 3-1(a) it seems that recycled glass particles can be categorized as a material with good to poor hydraulic conductivity, considering soil classification based on its permeability (Terzaghi et al., 1996). The various results of hydraulic conductivity tests on recycled glass obtained by different research teams seems to be due to the particle gradation of glass sources (Disfani, 2011). From Figure 3-1(a), it is obvious that the hydraulic conductivity values for the coarser glass particles are a little higher than those of finer particles (CWC, 1998; FHWA, 1998; Pennsylvania, 2001; Wartman et al., 2004b). The permeability of a granular soil is influenced by its particle size distribution and especially by finer particles. The smaller the particles, the smaller the voids between them, and therefore the resistance to flow of water increases with decreasing particles size (i.e. the permeability decreases) (Head, 1994).

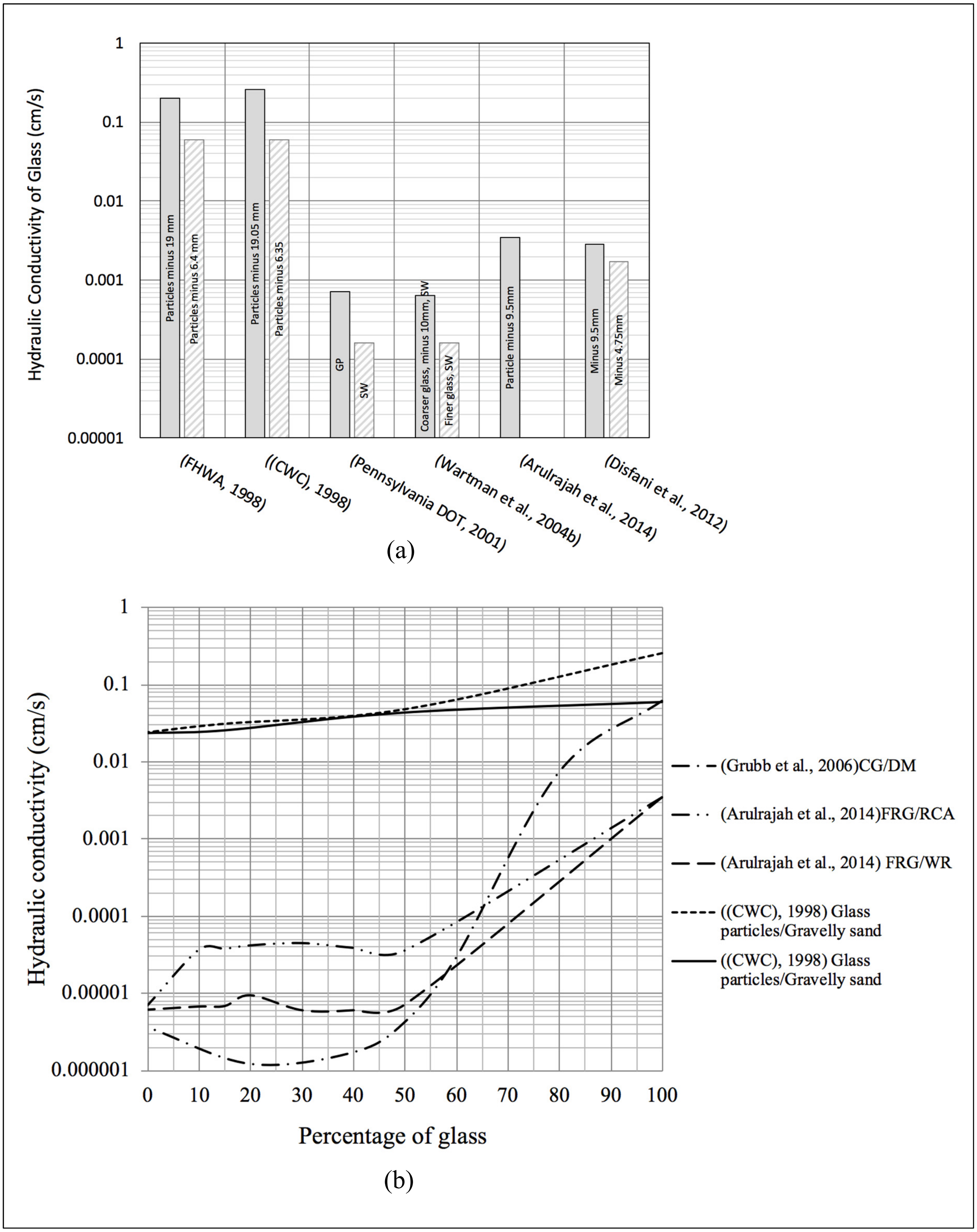

Figure 3-1 (a) The results of hydraulic conductivity test of 100% glass particles based on different researchers (b) Hydraulic conductivity versus percentage of recycled glass

Figure 3-1(b) presents the effect of recycled glass contents on the hydraulic conductivity of blends of recycled glass with other materials based on previous studies. It can be seen that recycled glass particles generally enhance the permeability of mixture. The results of studies by CWC (1998) indicate that the hydraulic conductivity values of samples (recycled glass particles with gravelly sand) increase with increasing glass content and glass size, as can be seen in Figure 3-1(b). Grubb et al. (2006b) evaluated the hydraulic conductivity of blends of crushed glass with dredged materials for different ratios of glass to dredged materials (20/80, 40/60, 50/50, 60/40, and 80/20 crushed glass (CG)/dredged materials (DM) blends). As can be seen in 3.1(b), the 20/80 and 40/60 CG/DM blends showed lower hydraulic conductivity values than 100% DM. This trend is because of the increased density that appeared prior to hitting 50% of CG. However, adding 60% to 80% CG to DM increased the hydraulic conductivity values of blends (Grubb et al., 2006b).

Also, based on studies on hydraulic conductivity of FRG/WR and FRG/RCA conducted by Arulrajah et al. (2014), FRG has the highest hydraulic conductivity and its permeability is similar to sand. Hydraulic conductivity values of FRG/WR, FRG/RCA and RCA are characterized as low-permeability materials due to higher fine size content of WR and RCA in blends (Arulrajah et al., 2014).

3.4.7 Thermal Properties of Recycled Glass

Information about thermal properties of pavement soils and materials are necessary for evaluation of thermal conditions within the pavement system. These properties include thermal conductivity, heat capacity, latent heat of fusion, and thermal diffusivity. The thermal regime in pavement is affected by moisture in pavement materials which directly affects the thermal conductivity and heat capacity of pavement. Also, a great amount of heat is produced or absorbed by moisture in pavement material (Doré and Zubeck, 2009). Using recycled glass particles due to their low thermal conductivity seems to reduce frost depth penetration in pavement structures in cold regions (FHWA, 1998).

Soundness of aggregates, which is their resistance to the forces of weathering, is an important parameter relating to roadwork materials (CWC, 1998). Frost susceptibility of aggregates is an important design parameter in roadwork through cold regions where there are serious frost penetration below geotechnical structures like pavement (Henry and Morin, 1997). Henry and Morin (1997) studied frost susceptibility of 100% and 30% of crushed glass by weight blended with two kinds of aggregate, Perry stream gravel classified as SW and Concord crushed gravel classified as SP. Two ideas were considered in their study, glass could be a source of fines and it could cause the aggregates to wear to finer particles due to traffic loading. The results indicated that glass has negligible to very low frost susceptibility and did not increase the susceptibility of aggregates.

The results of research conducted by Henry and Morin (Henry and Morin, 1997) indicated that the fine particles within recycled glass aggregate do not clump and retain water similar to fine particles in natural aggregates. So, glass aggregate is expected to retain less water, and this could be a reason for lower frost susceptibility (CWC, 1998). Wartman et al. (2004b) studied glass particle breakdown and decomposition due to freezing-related expansion of water using freeze-thaw tests. Up to 120 cycles of repeated freezing and rapid thawing (heating-induced) were applied to some specimens of crushed glass. After measuring the grain size distribution after freezing and thawing, small amounts of material were lost during sieving procedures. So, crushed glass is not susceptible to freeze-thaw related degradation (Wartman et al., 2004b).

3.5 Conclusion

This paper provides insight into the potential use of recycled glass particles in pavement structures. A thorough review on reusing recycled glass particles and their effects on improving pavement structure behavior was conducted. The results of different studies were compared with each other and some tables was presented for better understanding the effects of recycled glass on different characteristics of its blends with other materials. Based on the results of this study, the following conclusions are drawn:

The different research teams concluded that using recycled glass particles with other materials generally tends to enhance the behavior of blends. The engineering properties of recycled glass generally are similar to natural aggregates. The characteristics of recycled glass particles indicated that glass can be used for many road applications like base and subbase courses.

The gradation of most recycled glass particles proved that crushed glass is classified as well graded sand or gravel materials. The specific gravity of recycled glass particles was within the range of 2.41 to 2.54 which is lower than the typical values of most soils.

Based on compaction tests, the moisture-density trend of recycled glass is similar to that of natural aggregates with a bit difference in its shape which indicates relatively less sensitivity of recycled glass particle compaction to moisture content. The typical modified dry densities of glass particles were measured between 17.5-19.5 $kN/_{m^3}$ with optimum water contents of 5.5 to 11.2%.

The CBR values for MRG, with maximum size of 9.5 mm, showed higher values than FRG, with maximum size of 4.5 mm. Also, CBR values decrease with higher levels of recycled glass particles. The results of LA abrasion testing proved that recycled glass particles were considered as materials with good durability in road application, with the amounts in range of 24.25 to 42%. However, the soundness of recycled glass is not as good as that of natural crushed rock.

Based on direct and triaxial shear tests the values of friction angle of recycled glass particles are comparable to those of dense and coarse natural aggregates with negligible cohesion. Also, recycled glass particles have a lack of cohesion which affects shear strength. Furthermore, the values of friction angle of MRG samples showed higher amounts than those of FRG samples.

Glass particles are considered to have medium to low hydraulic conductivity in accordance with Terzaghi's classifications. The permeability of recycled glass particles categorized glass as a relatively free draining material and could have satisfactory performance in filtration and drainage applications.

Although recycled glass particles were perceived to have many drainage and strength applications, shortage of information about the effects of recycled glass on thermal behavior of its blends with natural aggregates prevents its widespread use in road applications in cold regions. In cold regions like Canada generally frost action affects the behavior of pavement structures. Occurrence of frost action, which includes frost heave and thaw weakening, is a result of the presence of three conditions, moisture in the pavement structure, cold temperature and frost susceptible soil. Recycled glass needs to be evaluated as a potential material to mitigate the effect of frost action in pavement structures. Furthermore, a thorough study is required to be conducted to evaluate recycled glass as an aggregate for use in pavement structures considering three aspects, including hydraulic, thermal and mechanical. This research team aims to concentrate on this issue and we will publish the results in the near future.

CHAPTER 4

PHYSICAL AND HYDRAULIC PROPERTIES OF RECYCLED GLASS AS GRANULAR MATERIALS FOR PAVEMENT STRUCTURE

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4.1 Abstract

The use of alternative materials in the construction industry is gaining popularity. This substitution of material aims to reduce the environmental impact related to energy consumption, soil and water pollution, green gas emission, waste disposal, and global warming. With these goals in mind, an innovative method of recycling uses recycled glass (RG) as an aggregate in pavement structures. However, the widespread use of RG as a substitute is impeded by insufficient knowledge on the geotechnical characteristics of RG. This research investigated the effects of using RG as a granular base aggregate specifically in the hydraulic aspect. Four size ranges of RG were considered, between 0.08mm and 5mm, in comparison with limestone aggregate as the reference aggregate. The experimental program included shape property, water absorption, specific gravity, compaction, hydraulic conductivity, and water retention. The existing methods to predict saturated hydraulic conductivity were also assessed. The research findings indicated that RG with negligible water absorption and medium degree of permeability could replace up to 100% of the fine fraction of MG20, 0-5mm, of base course aggregate without reducing the hydraulic

conductivity. Furthermore, RG showed better drainability than limestone aggregate, which contributes the performance of base/subbase aggregate in the presence of water.

4.2 Introduction

Recycling and reusing waste materials in engineering application is an important part of the sustainable construction principle. One of the objectives of Quebec's government, regarding sustainable development policy for the year 2015, was to recycle 70% of materials such as paper, carton, plastic, metal, and glass (Québec, 2011). To achieve this target, finding innovative solutions of reusing these recycled materials are necessary. The current study focuses on using recycled glass (RG) among the various recycled materials, as a partial replacement for unbound granular aggregate in pavement structure. The granular layers play the important roles in distributing the traffic loads through underlying layers. Furthermore, these layers need to provide adequate drainage since the seasonal variations of water content in structural layers and the freeze-thaw cycles, affect the pavement performance (Côté & Konrad, 2003). Hence, the unbound granular materials of pavements with good drainage capacity to dissipate any excess water and limit the moisture damage can contribute a satisfying global performance.

In the late 1960's and early 1970's, some investigations and field trials in the United States were conducted to evaluate the potential of using RG in hot mix asphalt with paving strips placed in some areas throughout the United States and Canada (FHWA, 1998). Nonetheless, using RG in granular base/subbase applications was not recognized in any documented demonstrations or commercial applications during that time. In 1993, Clean Washington Center's (CWC) published the results of Glass Evaluation Project in which using RG was introduced as granular aggregate in the pavement base and subbase (CWC, 1998). Subsequently, Federal Highway Administration (FHWA) (1998) came up with the potential for the use of crushed and screened glass as granular base materials. There are several studies on the suitability of using RG in concrete mixtures (Corinaldesi et al., 2005; Meyer & Xi, 1999; Taha & Nounu, 2008) and in asphalt layers (Halstead, 1993; Huang et al., 2007;

Lachance-Tremblay et al., 2017; Lachance-Tremblay et al., 2016; Landris & Lee, 2007; Meyer, 2001; Su & Chen, 2002; Taha & Nounu, 2008). Some researchers have also proposed using RG in other applications such as backfill material (Wartman et al., 2004b), and embankment fills (Grubb et al., 2006; Halstead, 1993). However, very little research has focused on applying RG in unbound materials of pavement layers, base/subbase (Arulrajah et al., 2013; CWC, 1998; FHWA, 1998; Ooi et al., 2008; Senadheera et al., 2005). Senadheera et al. (2005) indicate that RG could increase the strength of blends with caliche, which is a weathered limestone and used as a subbase material in many parts of Texas. The study conducted by Grubb et al. (2006a) reveals that the addition of RG improves the frictional strength of blends with dredged material. More recently, the findings of a research team on the usage of RG blended with other materials showed the potential application of RG in road construction including subbase, embankments material, and drainage media (Arulrajah et al., 2014; Disfani et al., 2011a). The previous studies revealed good hydraulic conductivity of RG and potential benefits in terms of drainage applications (Landris & Lee, 2007; Ooi et al., 2008; Wartman et al., 2004a-b). While both the hydraulic conductivity and the soil-water characteristic curve (SWCC) influence the movement of water in the pavement structures (Alonso, 1998), no data are established for SWCC of studied blends with RG.

In the documents of the local ministry of transportation, there is not any published regulation and specification that allow using RG in different roadwork applications as an alternative to natural aggregate. However, some recycled materials, containing asphalt or concrete, concrete brick, and clay brick, are permitted (BNQ, 2002). Hence, despite the fact that some researchers have investigated the geotechnical engineering suitability of RG, there is still a shortage of knowledge on the effect of using RG of various sizes on the mechanical and hydraulical performance of such pavement materials.

A research study was undertaken in this project to demonstrate the geotechnical performance of RG as granular base/subbase aggregate and to fill the gap in the geotechnical characteristics of RG. The main objective of this paper is to gain a better understanding of the efficiency of RG aggregate through a comprehensive series of laboratory tests, including shape property, water absorption, specific gravity, compaction, hydraulic conductivity, and water retention. Furthermore, the results of hydraulic conductivity of the studied materials are compared with predicted hydraulic conductivity by some existing models to suggest the most appropriate estimation methods.

4.3 Experimental program

The experimental program was divided into two parts. The first part was focused on studying the physical and hydraulic properties of the separate sizes of RG and crushed limestone aggregate. In the second part, the experimental tests were applied to trace the impact of RG on blends. In this regard, the studied materials and methods will be discussed in the following sections.

4.3.1 Materials

In the current research two types of materials are studied, including RG of particle size range of 0-5mm and crushed limestone aggregate of particle size range of 0-20mm, as the reference material. In the first part, RG aggregate were categorized in five groups, including very fine (VF) recycled glass, 0.08mm-0.63mm (VFRG); fine (F) recycled glass, 0.63mm-1.25mm (FRG); medium (M) recycled glass, 1.25mm-2.5mm (MRG); coarse (C) recycled galss, 2.5mm-5mm (CRG); and mixed-size recycled glass (mixed-size RG), 0.08mm-5mm. Figure 4-1 shows the different size category of RG. The same size categories were also examined for limestone aggregate, namely as VFFL, FFL, MFL, CFL, and mixed-size FL for very fine limestone, fine limestone, medium limestone, coarse limestone, and mixed-size limestone, respectively. In this study, FL is referred to fine fraction of limestone, 0-5mm.

Afterwards, three blends of RG and crushed limestone to meet the requirements for MG20 (standard granular base in Quebec) were evaluated (Figure 4-2). The fine fraction of MG20 (0-5mm) was replaced by RG with volumetric method, based on different ratio between 25% and 100% (Figure 4-3). In current study, the gradations of all blends were kept constant as the volumetric method of replacing RG for the exact size of the fine fraction of MG20 was followed.

Figure 4-1 Recycled glass particles with different size

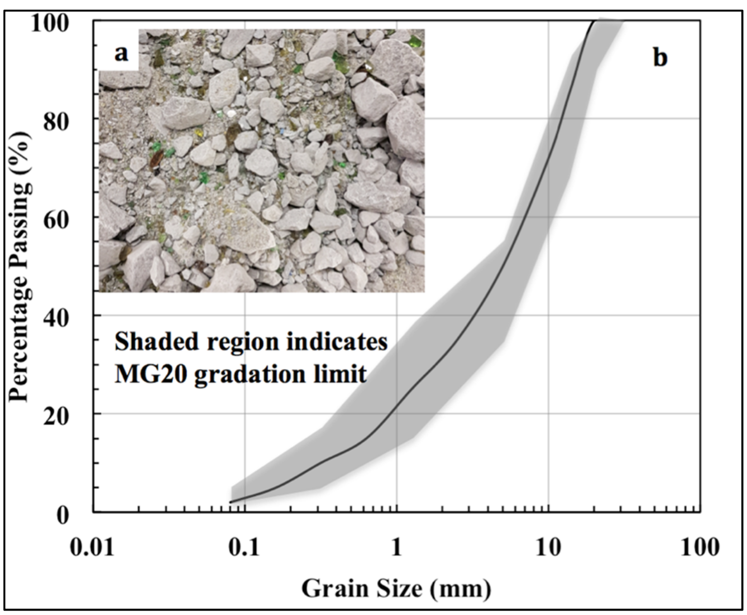

Figure 4-2 (a) MG20 blends with RG (b) Gradation curve for MG20

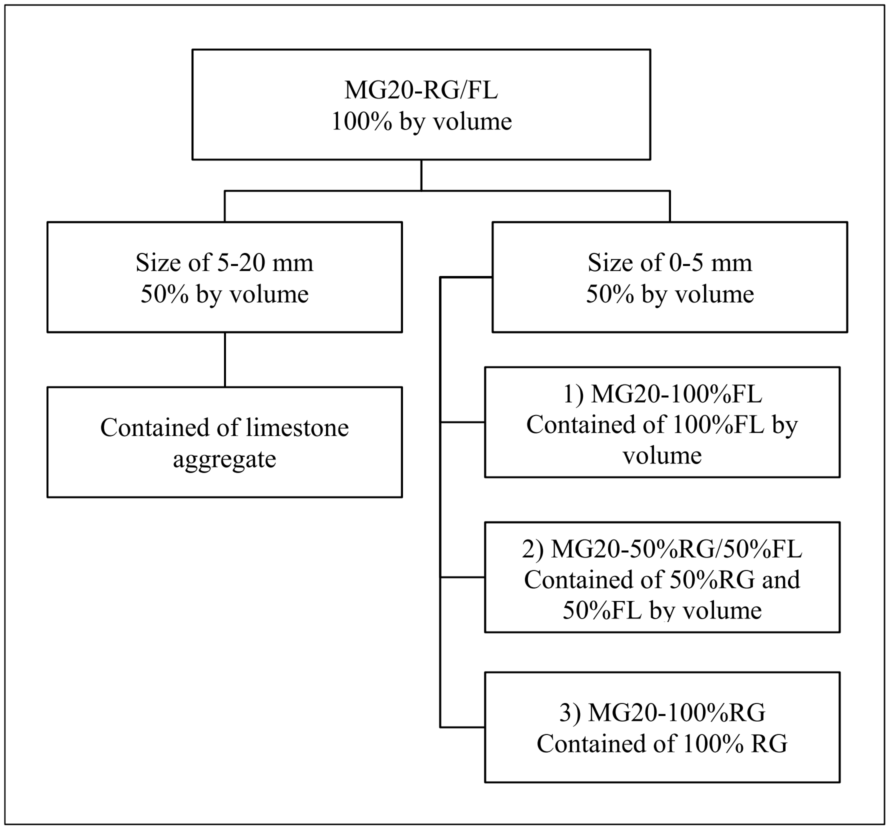

Figure 4-3 Size categories of three specimens for experimental study

4.3.2 2-2-Methods

Laboratory tests were conducted on RG, limestone aggregate, and their blends to investigate the effect of using RG on the performance of pavement unbound layers. These tests, which included some physical and hydraulic characterization tests, are illustrated in the following sections.

4.3.2.1 Shape properties

Using the X-ray computed tomography (CT) the approximate porosity of particles was estimated. The energy spectrum that defines the capacity of X-rays through materials was considered as 115 kV. The limestone and recycled glass particles were scanned at a resolution with the voxel size of 7.05 µm. The obtained images from X-ray CT were exported to Dragonfly software version 3.5 (Dragonfly, 2004), which is a platform for the intuitive inspection of multi-scale multi-modality image data. In the software, the volume of void spaces and the total volume of particles were detected as some gray spots and estimated in all thresholds of particles. The flow index test (MTMDET, 2015) was also applied to evaluate the shape properties of the aggregate.

4.3.2.2 Density of particle and water absorption

The particle density of aggregate was determined following ASTM D854 standard test method (ASTM, 2014b). The water absorption properties of aggregate were determined based on the ASTM C128 test method. Water absorption is described as the ratio of the mass of water held in the permeable voids of the particles to the oven-dried mass of the material (ASTM, 2015a).

4.3.2.3 Compaction

The maximum dry unit weight (γ_{dMAX}) and minimum dry unit weight (γ_{dMIN}) of RG and limestone aggregate were investigated using vibratory table based on ASTM D4253 and ASTM D4254, respectively (ASTM, 2016b, 2016c). The maximum unit weight of studied materials was determined by placing oven-dried material in a mold, applying a 14 KPa surcharge (dead weight) to the surface of the soil, and then vertically vibrating the mold, soil, and surcharge. A cam-driven vibrating table having a sinusoid-like time-vertical displacement relationship at a double amplitude of vertical vibration (peak-to-peak) of about 0.33 ± 0.05mm was used at a frequency of 60 Hz for 8.00 ± 0.25 minutes. The maximum unit weight is calculated by dividing the oven-dried mass of the densified soil by its volume (average height of densified soil times area of mold) (ASTM, 2016b).

4.3.2.4 Hydraulic conductivity

The hydraulic conductivity of the studied materials was determined based on the constant head method by ASTM D2434 (ASTM, 2006). The hydraulic conductivity is a property that describes how water flows through the material (Holtz & Kovacs, 1981). The specimens were compacted to reach 98% ± 2% of γ_{dMAX} based on compaction test data. The constant head permeability cell was used to conduct permeability test on the granular material which were compacted inside the permeameter. The rigid-wall plastic permemeter with the internal diameter of 100mm and 152mm were used to measure the hydraulic conductivity of studied materials with the maximum particle size of 5mm and 20mm, respectively.

4.3.2.5 Water retention

Water retention capacity of material is important to evaluate the drainability of pavement system. The SWCC describes the change in water content in function of the change in matric suction and can be drawn from experimental data of water content corresponding matric suction (Rahardjo et al., 2010). Matric suction is the difference between pore gas pressure and pore water pressure. In this study the pore gas pressure is air. It is possible to estimate the unsaturated hydraulic conductivity of a given soil from SWCC, since the direct measurmenets of unsaturated hydraulic conductivity is difficult. A pressure plate apparatus was used to evaluate SWCCs. The ceramic plate of apparatus had a maximum air entry (ψ_a) value of 100KPa. The ψ_a value corresponds to the matric suction at which air begins to enter into the material. The specimens were compacted to 98% ± 2% of γ_{dMAX} from modified compaction test. Based on the ASTM D6836 standard test method (ASTM, 2008), the pore gas pressure was increased step by step, while pore water pressure was maintained at zero. The water contents were determined under different values of matric suction, where equilibrium is established by monitoring water ceases to flow from the specimen. Numerous fitting equations have been suggested to represent the SWCC (Brooks & Corey, 1964; Fredlund & Xing, 1994; Van Genuchten, 1980). Equation (4.1) proposed by Fredlund and Xing (1994) provides the best fit for all soil types for matric suction values in the range of 0 to 1000000 KPa (Rahardjo et al., 2010). Leong and Rahardjo (1997) proposed $C(\psi)$ (Equation (4.2)) to be set to one (Equation (4.3)) to give better prediction of SWCC (Leong & Rahardjo, 1997).

$$\theta = C(\psi) \times \left[\frac{\theta_s}{\left[ln\left[e + \left(\frac{\psi}{a}\right)^n \right] \right]^m} \right] \tag{4.1}$$

where:

θ =volumetric water content at any suction,
θ_s=saturated volumetric water content,
a=suction related to the air-entry value of the soil (KPa),
e=natural number, 2.718 28,
m=soil parameter related to the residual water content,
n=soil parameter related to the slope at the inflection point on the SWCC,
ψ =soil suction (KPa), and
$C(\psi)$=correction function.

The correction function is defined as

$$C(\psi) = \left[1 - \frac{ln\left(1 + \frac{\psi}{\psi_r}\right)}{ln\left(1 + \frac{1000000}{\psi_r}\right)} \right] \tag{4.2}$$

$$C(\psi) = 1 \tag{4.3}$$

where:

ψ_r=suction corresponding to the residual water content, θ_r, where a large suction change is required to remove additional water from the soil.

The fitting parameters, a, n, and m define the shape of SWCC. Using a non-linear regression analysis, the model parameters are derived by adjusting the predicted values to the measured values using an iterative procedure.

4.4 Results and discussion

The characteristics of separate sizes of RG and crushed limestone aggregate and also the impact of using RG as an unbound granular aggregate on the hydraulic property of MG20 will be discussed in the following sections. Table 4-1 presents the properties of studied specimens. The grain size distribution parameters including D_{max} (maximum particle diameter), C_u (coefficient of uniformity, which is the ratio of $\frac{D_{60}}{D_{10}}$) , C_c (coefficient of curvature, which is the ratio of $\frac{D_{30}^2}{D_{60} \times D_{10}}$, where D_{10}, D_{30} and D_{60} are the particle diameters corresponding to 10%, 30% and 60% finer on the cumulative particle-size distribution curve), percentage of gravel (4.75mm-75mm), sand (0.075mm-4.75mm) and fines (0-0.075mm), and USCS symbol are summarized in Table 4-1. The five categories of both RG and FL (C, M, F, VF, and Mixed-size) have equal amount of sand, gravel, and fines content, enabling them to be classified as poor-graded sand (SP). The classification of MG20 blends is well-graded sand (SW) due to the approximately equal contents of sand, gravel, and fines.

4.4.1 Shape properties, density of particle and water absorption

The angularity and surface texture of RG and limestone were indirectly assessed with the flow index test (MTMDET, 2015). As it can be observed in Table 4-2, the flow index of limestone is higher than RG.

Table 4-1 Studied specimen properties

	C	**M**	**F**	**VF**	**mixed -size**	**MG20-100%FL**	**MG20-50%RG/ 50%FL**	**MG20-100%RG**
USCS classification	SP	SP	SP	SP	SW	SW	SW	SW
D_{max}, mm	5.0	2.5	1.25	0.63	5.0	20	20	20
D_{10}, mm	2.75	1.37	0.69	0.11	0.21	0.31	0.33	0.35
C_u	1.45	1.45	1.45	2.86	8.33	23.08	22.73	22.06
C_c	0.96	0.96	0.96	0.74	1.55	1.54	1.57	1.94
Fines content, %	0.0	0.0	0.0	0.0	0.0	2.0	1.9	1.9
Sand content, %	100	100	100	100	100	48	46.8	45.5
Gravel content, %	0.0	0.0	0.0	0.0	0.0	50	51.3	52.6
Mass corresponding percentage of RG	-	-	-	-	-	0.0	23.1	47.4

It was accepted that the higher flow index is due to the higher angularity or rougher surfaces of particles or the combination thereof (MTMDET, 2015). This point was investigated using X-ray CT to verify the shape of particles. With X-ray CT, it is possible to determine the complete and three-dimensional shape of particle (Erdoğan, 2005). Figure 4-4(b) and (c) show the scanned limestone and recycled glass aggregates using X-ray CT. It seems that the angularity of RG is visually less than limestone. From Figure 4-4(d) and (e), which show the imported images into Dragonfly software, the gray spots on the limestone image confirm some porosity in the nature of particles but the RG particle image shows a non-porous smooth texture. The porosity value based on Dragonfly software (Dragonfly, 2004) was measured around 2.7% for limestone particle and negligible for RG particle.

Table 4-2 Flow indexes of aggregate based on flowing tests

Size Category	**Recycled glass**	**Limestone**
$1.25\text{mm} < \text{d} < 2\text{mm}$	104	149
$0.63\text{mm} < \text{d} < 1.25\text{mm}$	82	115
$0.315\text{mm} < \text{d} < 0.63\text{mm}$	80	94

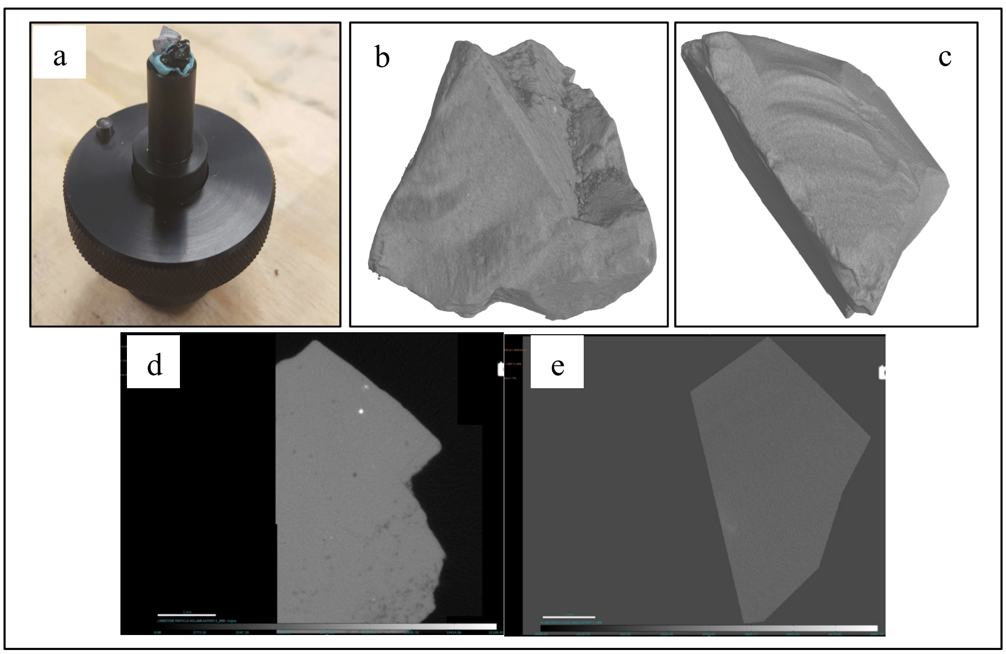

Figure 4-4 (a) RG and limestone particles for X-ray CT (b) 3D image of limestone (c) 3D image of RG (d & e) gray spots detected in limestone and RG particles based on Dragonfly software, respectively

The aggregate shape properties are the important parameters to predict the properties of the mixes (Erdoğan, 2005). One of the most important properties of aggregates is the porosity, which is a ratio of the pore volumes to the total volume of the particle. The pore characteristics of aggregates can affect the moisture flow into and out of aggregates, water absorption, and the development of pressure during a freeze-thaw cycle (Tarrer & Wagh, 1991). The negligible porosity of RG particle leads to negligible water absorption that was observed in the water absorption tests. Therefore, the negligible water absorption of RG prevents water from being absorbed and kept by the particles. However, the water absorption of limestone aggregate was estimated 0.8-1.5% for different size range. The water absorption values of fine aggregate were found slightly higher than coarser ones. The fine particles with larger specific surface absorb more water than the coarse one (Arulrajah et al., 2013). The previous studies on the RG support the results of physical properties obtained in this research. They illustrate the smooth impermeable surface of the RG is the reason for negligible water absorption value of RG (Ali et al., 2011; Taha & Nounu, 2008).

The results of specific gravity tests indicated that the limestone aggregate had higher values (2.761) than RG aggregate (2.491). The values achieved for the specific gravity of RG in this study are similar to the values reached by Wartman et al. (2004), 2.48–2.49, FHWA (1998), 2.49–2.52, and CWC (1998), 2.49.

4.4.2 Compaction

Figure 4-5(a) and (b) present γ_{dMAX} and γ_{dMIN} of RG and limestone aggregate for the different sizes. It can be observed from Figure 4-5 that there were no significant changes in either γ_{dMAX} or γ_{dMIN} of specimens of different size range, including C, M and F, for both FL and RG aggregate. VF demonstrated somewhat higher value of γ_{dMAX} and γ_{dMIN} for both RG and FL. From Figure 4-5, the values of γ_{dMAX} obtained for RG specimens are 9 to 13% lower than the values achieved for FL with the same soil classification. Similarly, γ_{dMIN} of RG shows lower values than FL. In order to compare the compaction aptitude of studied materials, the normalized dry density of specimens was calculated using Equation (4.4).

$$\rho_{dn} = \frac{\rho_{dMAX}}{\rho_s} \qquad \text{Equation (4.4)}$$

Where, ρ_{dn} is normalized dry density of specimen (without unit), ρ_{dmax} is maximum dry density ($\frac{gr}{cm^3}$), ρ_s is particle density ($\frac{gr}{cm^3}$).

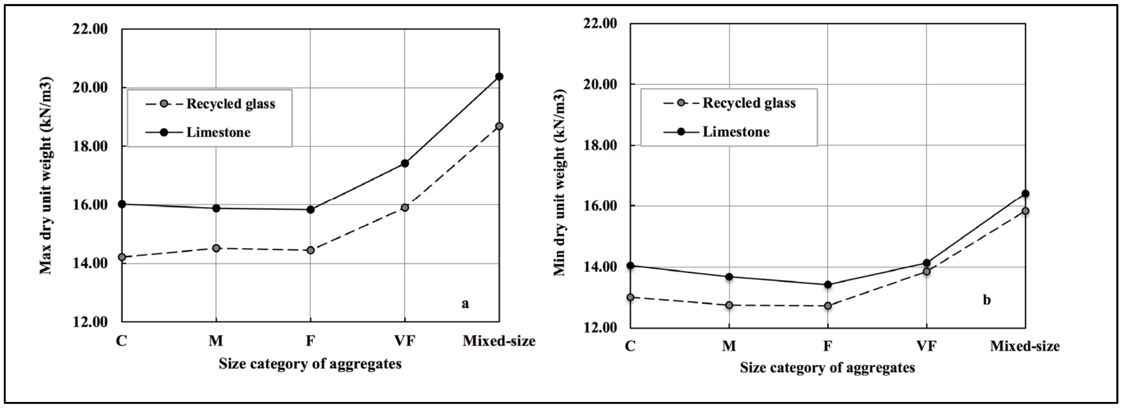

Figure 4-5 (a) γ_{dMAX} for RG and FL (b) γ_{dMIN} of RG and FL based on Vibratory compaction test

Table 4-3 presents the normalized dry density of studied materials and the compaction results. It can be seen that the differences between ρ_{dn} of studied RG and limestone are not significant. Hence, the reduction of γ_{dMAX} of RG compared to limestone can be explained by the lower specific gravity of RG ($\mathrm{G_s}$=2.491) than limestone ($\mathrm{G_s}$=2.761).

The result of vibratory compaction of mixed-size RG specimen is close to the values reported for RG (aggregate with the size of 0-4.75mm) by previous studies. The typical values of modified dry unit weight of RG are reported between 17.5 $^{kN}/_{m^3}$-19.5 $^{kN}/_{m^3}$ (Arulrajah et al., 2014; Disfani et al., 2011a; Amlashi et al., 2015).

The particle size distributions of the studied materials, before and after compaction, are shown in Figure 4-6(a) and (b). The after-compaction grading curves demonstrate that negligible breakdown has occurred during vibratory compaction for both two materials.

Table 4-3 Compaction results of studied materials

Material	**Size category**	$\gamma_{dMAX}, \frac{kN}{m^3}$	ρ_{dn}, **without unit**	**Porosity (n)**
RG	CRG	14.22	0.582	0.42
	MRG	14.51	0.594	0.41
	FRG	14.45	0.592	0.41
	VFRG	15.91	0.651	0.35
	Mixed-size	18.69	0.765	0.23
FL	CFL	16.02	0.592	0.41
	MFL	15.89	0.587	0.41
	FFL	15.84	0.585	0.42
	VFFL	17.42	0.643	0.36
	Mixed-size	20.38	0.753	0.25

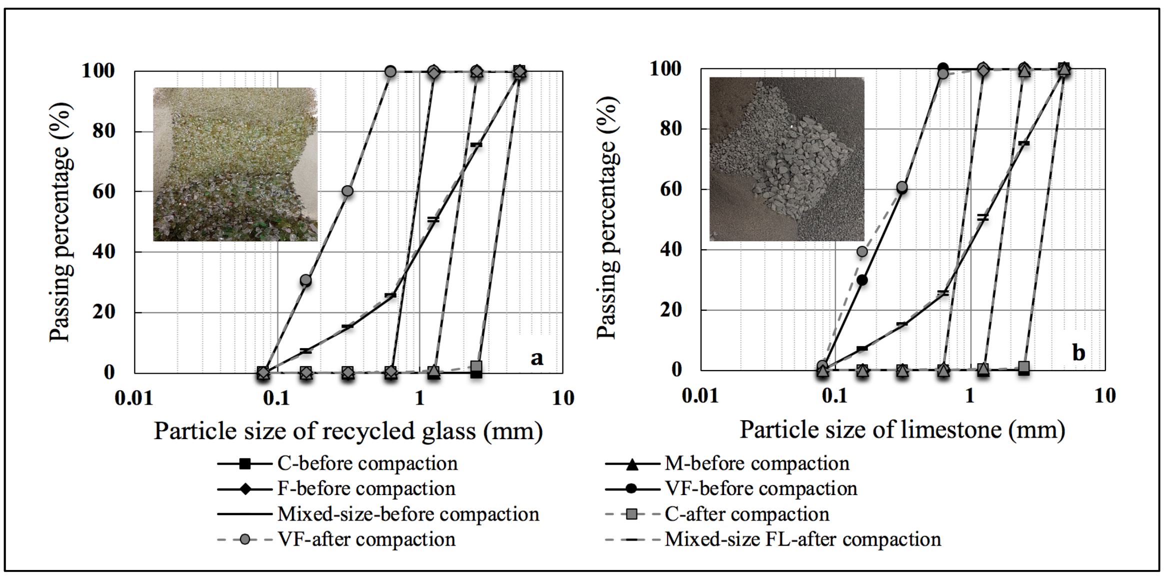

Figure 4-6 Gradation curves of studied aggregate before and after vibratory compaction test (a) RG (b) FL

4.4.3 Hydraulic conductivity of separate sizes of aggregate

Figure 4-7 and Table 4-4 present the results of the hydraulic conductivity tests performed on RG and FL in the laboratory. The hydraulic conductivity (K) values of both materials follow a downward trend by decreasing the particle size. Figure 4-7 shows clearly that the smaller the size of particles the smaller the hydraulic conductivity values are for the specimens. The result of this study are in agreement with Murray (1995) who represented the size of aggregate as one of the factors influencing the hydraulic conductivity (Murray, 1995). From Table 4-4 it can be seen that the values of porosity for separate size aggregate (C, M and F) are higher than those of mixed size aggregate (VF and mixed-size). Hence, a higher porosity leads into the higher values of hydraulic conductivity for separate sizes (Ghabchi et al., 2013; Hatanaka et al., 2001; Khoury et al., 2010; Shah, 2007).

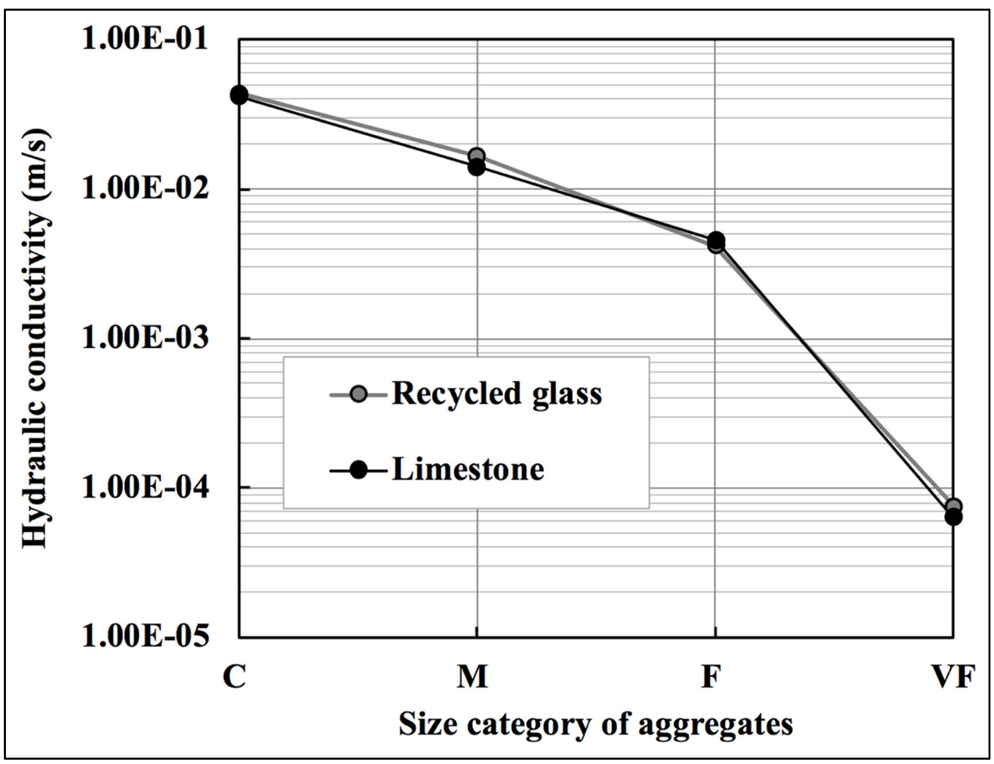

Figure 4-7 Hydraulic conductivity of aggregate with different size categories

Table 4-4 Results of hydraulic conductivity tests on RG and FL

Material	**Size category**	$\gamma_d, \frac{kN}{m^3}$	$\gamma_{dMAX}, \frac{kN}{m^3}$	$\frac{\gamma_d}{\gamma_{dMAX}}$	**Void ratio, %**	**Porosity, %**	**Saturation degree, %**	$K, m/s$
RG	CRG	14.19	14.22	1.00	0.72	41.91	100	4.40E-02
	MRG	13.97	14.51	0.96	0.75	42.83	100	1.67E-02
	FRG	14.43	14.46	1.00	0.69	40.95	100	4.14E-03
	VFRG	15.29	15.91	0.96	0.60	37.41	99.8	7.55E-05
	Mixed-size	17.92	18.69	0.96	0.36	26.66	100	1.94E-04
FL	CFL	15.71	16.02	0.98	0.72	41.98	100	4.13E-02
	MFL	15.58	15.89	0.98	0.74	42.45	100	1.41E-02
	FFL	15.23	15.84	0.96	0.78	43.75	99.9	4.53E-03
	VFFL	17.11	17.42	0.98	0.58	36.81	99.6	6.31E-05
	Mixed-size	20.18	20.38	0.99	0.34	25.46	100	1.57E-04

The ratio of K values of RG on FL for the same grain size (C, M, F, and VF) is between 0.92 to 1.19. It means that the difference of hydraulic conductivity between RG and FL for different size categories is not significant. It can be explained by the fact that there is not much difference between the porosity of RG and FL for different size categories (Table 4-4). This ratio increases slightly for mixed-size aggregates, around 1.23. It means that RG shows slightly higher values of K than FL or the mix of sizes. The smoother surface of RG, based on the results of flowing tests, can contribute to enhancing its hydraulic conductivity potential in mixed size aggregates.

Therefore, all four-size ranges of RG prove high potential to replace the natural aggregate in pavement structure regarding the hydraulic conductivity. Based on the classification of hydraulic conductivity by Terzaghi et al. (1966), the separate sizes of RG are categorized in the high degree of permeability and the mix of sizes in the medium degree (Terzaghi et al., 1996).

Arulrajah et al. (2013) reported the K value one order of magnitude smaller than K value of mix sizes of RG aggregates in this study (Arulrajah et al., 2013). The reason for this difference can be explained based on the different size-gradation. Furthermore, RG aggregate studied by Arulrajah et al. (2013) included 5.4% of fines (particles smaller than 0.075mm), which can again explain the smaller value of K. The result of K value of RG in this paper agrees with the study conducted by Grubb et al. (2006a), as the gradation of RG in both studies is similar with negligible fines. The FHWA (1998) reported the K values of 6.0E-04 m/s for RG (with a maximum size of 6.4mm), which is higher than the studied RG in this paper due to the bigger size of glass. The measured values of K propose that RG is a relative free draining material and can act properly in filtration and drainage applications (Wartman et al., 2004a-b).

K values of soils can be either measured from field and laboratory tests or predicted by existing models. Measurements of values through tests are time consuming and more expensive than prediction by the existing models (Chapuis, 2012). Therefore, in most projects, the use of simple estimation model for predicting K values are often selected. In next section the predicted K values based on some models are compared with the laboratory-measured values for FL and RG aggregates.

4.4.3.1 Assessing predictive methods for hydraulic conductivity of studied materials

One of the existing methods to estimate the saturated hydraulic conductivity of aggregate is using empirical relationship (Chapuis, 2012). For non-plastic soils, most predictive models use effective grain size (d_{10}) and the porosity (n) or the void ratio (e). Chapuis (2012) highlighted seven predictive models among the existing models as having good potential to estimate the hydraulic conductivity values of non-plastic soils. Therefore, in this paper, K values of studied materials were estimated based on those equations to select the most appropriate models for RG and FL in engineering applications. The models and the required parameters for each predictive model are illustrated in Table 4-5. The model proposed by Hazen (1892) is appropriate for soils in loose condition. Taylor (1948) suggested a model to estimate K as a function of the void ratio. Using two aforementioned models known as Hazen-Taylor, the hydraulic conductivity can be estimated for any void ratio (Chapuis, 2012).

The predictive capacities of mentioned models were compared using the previously described laboratory data of hydraulic conductivity tests. The graph of log (predicted K) versus log (measured K) is shown in Figure 4-8. Three models provided fair predictions, including Hazen-Taylor, Kozeny-Carman, and Chapuis (2004), usually between one third (y = x/3) and three (y = 3x) times. The values predicted by Mbonimpa et al. (2002), were overestimated by a factor of 20 to 200 while the method of Terzaghi (1925) predicted underestimated values. Other models estimated out of range values for studied materials as it can be noted from Figure 4-8. Hence, these models are not suggested for estimating K values for studied materials.

4.4.4 MG20 blends with recycled glass

In this part the results of experimental tests, including K and SWCC, to determine the impact of RG on the water movement of blends in unbound layers of pavement are presented.

Table 4-6 presents the results of compaction and K on MG20 blends with RG. It can be observed that γ_{dMAX} of MG20 blends decreased with increasing RG contents. The lower specific gravity of RG than limestone aggregate can explain this trend. Based on results, replacing fine fraction of MG20, 0-5mm, by RG improves K of blends. As shown in Table 4-6, by increasing RG from 0 to 50% in MG20, K increases by the ratio of 1.38 ($\frac{K_{50\%RG-50\%FL}}{K_{100\%FL}}$). This ratio is around 1.52 for increasing RG up to 100% in fine fraction of MG20 ($\frac{K_{100\%RG}}{K_{100\%FL}}$).

Table 4-5 Predicting K values of soils based on the empirical models

Author(s)	**Model**	**Characteristics of the predictive model**
Hazen (1892)	$K_{sat}(e_{max})\left(\frac{cm}{s}\right) = 1.57\left(\frac{d_{10}}{1mm}\right)^2\left[0.7 + 0.03\left(\frac{T}{1^{0C}}\right)\right]$	T, water temperature in degrees Celsius; e_{max}, max void ratio.
(Terzaghi, 1925)	$K_{sat}\left(\frac{cm}{s}\right) = C_0\frac{\nu_{10}}{\nu_T}\left(\frac{n-0.13}{\sqrt[3]{1-n}}\right)^2 d_{10}^2$	Constant C_0 for smooth rounded and irregularly shaped grains are 8 and 4.6, respectively; $\frac{\nu_{10}}{\nu_T}$, the viscosity ratio of water; n, porosity.
(Taylor, 1948)	$K_{sat}(e)\left(\frac{cm}{s}\right) = A\frac{e^3}{1+e}$	Coefficient A has a specific value for each soil.
Hazen-Taylor	$\frac{K_{sat}(e)}{K_{sat}(Hazen)} = \left(\frac{e^3}{e_{max}^3}\right)\left(\frac{1+e_{max}}{1+e}\right)$	Based on a combination of two equations, Hazen and Taylor
Kozeny-Carman (Wyllie & Gardner, 1958)	$K_{sat} = C\frac{g}{\nu_w\rho_w}\frac{e^3}{(1+e)S_S^2G_s^2}$ $S_S(d) = \frac{6}{\rho_s}\sum\frac{P_{No.D-}P_{No.d}}{d}$ $P_{No.D-}P_{No.d}$ = percentage of solid mass smaller than size D (PNo. D), and larger than the next size d (PNo. d); ρ_s, density (kg/m3)	C, a constant, for angular aggregate=0.2; g, the gravitational constant $\frac{m}{s^2}$; ν_w, viscosity of water (Pa.s); S_S, surface specific (m^2/kg)
(Navfac, 1974)	$K_{sat}\left(\frac{cm}{s}\right) = 10^{1.291e-0.6435}(d_{10})^{10^{0.5504-0.2937e}}$	
(Shahabi et al., 1984)	$K_{sat}\left(\frac{cm}{s}\right) = 1.2C_U^{0.735}d_{10}^{0.89}\frac{e^3}{1+e}$	C_U, the coefficient of uniformity
(Mbonimpa et al., 2002)	$K_{sat}\left(\frac{cm}{s}\right) = C_G\frac{\gamma_w}{\upsilon_w}C_U^{1/3}d_{10}^2\frac{e^{3+x}}{1+e}$	$C_G = 0.1$, $\gamma_w = 9.8$ kN/m3, $x = 2$
(Chapuis & Aubertin, 2003)	$K_{sat}\left(\frac{cm}{s}\right) = 2.4622\left(\frac{d_{10}^2e^3}{1+e}\right)^{0.7825}$	

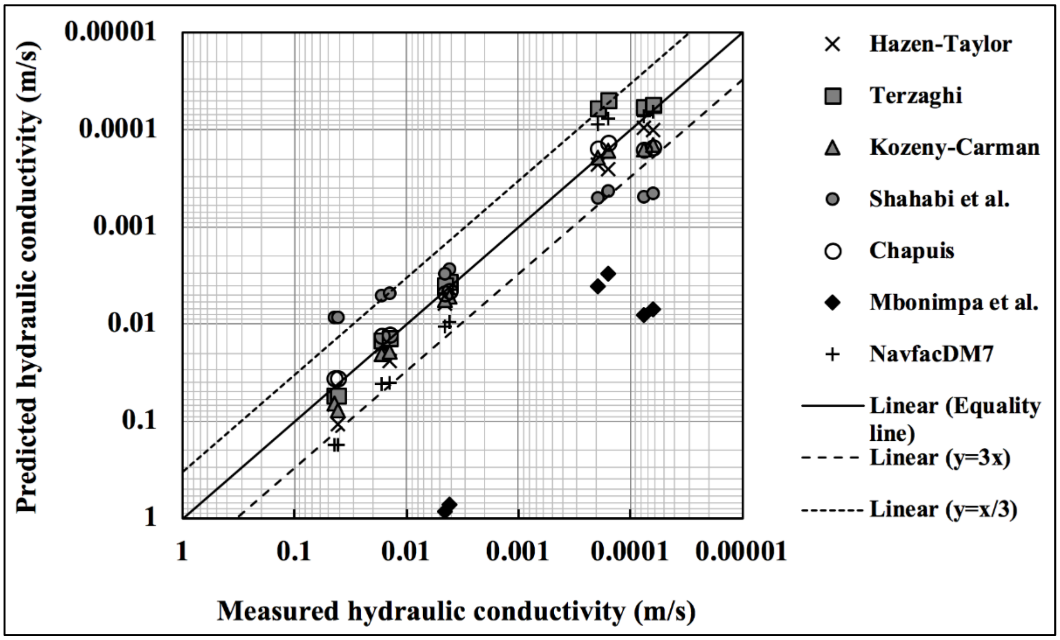

Figure 4-8 Measured versus predicted K for RG and FL, using proposed models

Côté and Konrad (2003) indicated that K is significantly affected by the overall porosity and the fines content ($d < 0.075mm$). Increasing fines proportion and decreasing porosity result in decreasing K. Since the differences between porosity and fines content of three studied blends are not significant, it seems that the mineralogy of material may influence the K values of aggregate. A close examination of data by Côté and Konrad (2003) revealed that for a given porosity and fines content, the specific surface areas of fines (S_{sf}) expressed in $\frac{m^2}{g}$ seems to be the main factor influencing the K. Côté and Konrad (2003) highlight the relationship between the pore-size distribution index (λ) and the S_{sf} of fines since increasing values of S_{sf} leads to decreasing values of λ. This is logic considering the fact that the variations of λ is a function of the particle dimensions of soils. In this study S_{sf} of studied materials was evaluated using the methylene blue method (CAN/BNQ, 1982). Based on the results, glass and limestone fines ($d < 0.08mm$) showed the values of 1.68 and 6.22 $\frac{m^2}{g}$ for S_{sf}, respectively. Therfore, the blends with higher proportion of RG have the lowest values of S_{sf} and the highest K values. The K trend of RG versus limestone aggregate in the current study are comparable to crushed granite (with $S_{sf} = 2.3\frac{m^2}{g}$) versus crushed limestone (with $S_{sf} = 11.4\frac{m^2}{g}$) in the study by Côté and Konrad (2003). Côté and Konrad (2003) explain that crushed granite with lower values of S_{sf} has higher values of K than crushed limestone. The specific surface area and porosity of fines are the principal factors that are considered for the tortuosity of flow and space available for water to flow (Côté & Konrad, 2003).

Table 4-6 Results of K tests on MG20 blends with RG

Materials	**MG20-100%FL**	**MG20-50%RG/50%FL**	**MG20-100%RG**
$\gamma_{dmax}, {kN}/{m^3}$	22.94	21.70	20.90
$\gamma_d, {kN}/{m^3}$	22.25	21.18	20.48
${\gamma_d}/{\gamma_{dmax}}$	0.97	0.98	0.98
Void ratio	0.22	0.25	0.26
Porosity, %	17.82	19.83	20.49
Degree of saturation, %	97.9	98.2	97.7
$K, {m}/{s}$	1.80E-04	2.49E-04	2.74E-04

From the results presented in Table 4-6, it can be seen that all blends of RG and limestone aggregate show a medium degree of permeability based on Terzaghi et al. (1966). However, Arulrajah et al. (2013) categorized the blends of waste rock-RG and recycled concrete-RG as low-permeable materials despite the high-estimated K value of RG (3.5E-05 m/s). Higher fines content ($d < 0.075mm$) of the studied blends (5.8-12%) in comparison with the very low content of fines in pure RG (2.8%) explained well the observed trends (Arulrajah et al., 2013). In the current study, the gradations of the different blends were kept constant to investigate the effect of RG on the hydraulic behaviour. Therefore, replacing a ratio of fine fraction of MG20 by RG did not change the fines content of blends, as replacement of aggregates with the volumetric method of the exact size of the fine fraction was followed.

As explained in the methodology section, water retention properties of RG blends, which is one of the important parameters affecting water movement in pavement structure, are identified by SWCC. Figure 4-9 shows the SWCCs of three studied blends, as measured with the pressure plate apparatus tests. This procedure allows describing the change in volumetric water content with respect to the change in matric suction.

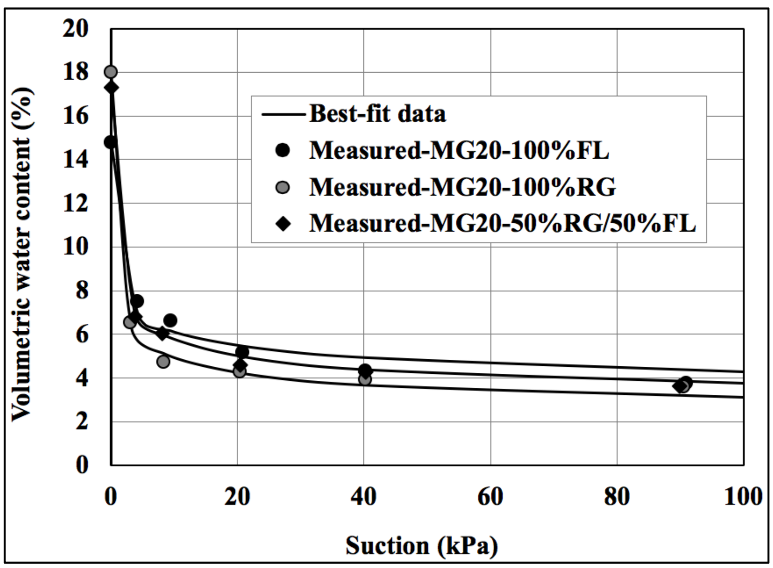

Figure 4-9 Measured SWCC with the pressure plate apparatus and best-fit curves to the experimental data based on Fredlund and Xing's model for MG20 blends (Fredlund and Xing 1994)

From Figure 4-9, the shapes of SWCC for blends with RG are similar to the corresponding shapes for MG20-100%FL. It can be seen that with decreasing the volumetric water content the value of suction tends to be increased for all three blends. The equation proposed by Fredlund and Xing (1994), with correction factor of $C(\psi)=1$ as suggested by Leong and Rahardjo (1997), was used for fitting the experimental data of SWCC. As shown in Figure 4-9, the Fredlund and Xing (1994) model provides reliable fits for the studied blends. The fitting parameters for the studied blends are summarized in Table 4-7. The root-mean-square error (RMSE) value, which is a measure of the differences between predicted values by model and measured values, was calculated to evaluate the capacity of Fredlund and Xing's equation to predict SWCCs (Fredlund and Xing 1994). The low values of RMSE, which are presented in Table 4-7, indicates that the best-fit parameters of the Fredlund and Xing's equation closely describe the SWCC data obtained from laboratory tests.

Table 4-7 Fredlund and Xing's best-fit parameters

Material	$\gamma_d, \frac{kN}{m^3}$	$\frac{\gamma_d}{\gamma_{dmax}}$	**Void ratio**	a **(KPa)**	n	m	**RMSE**
MG20-100%FL	23.04	1.00	0.18	0.235	0.327	1.489	0.004
MG20-50%RG/50%FL	21.85	1.01	0.21	0.174	0.407	1.509	0.002
MG20-100%RG	21.12	1.01	0.22	0.110	0.437	1.559	0.003

m=soil parameter related to the residual water content

n=soil parameter related to the slope at the inflection point on the SWCC

Based on the previous studies the parameter "a" is approximately related to the ψ_a value (Fredlund & Xing, 1994; Gallage & Uchimura, 2010). The ψ_a values of a material demonstrate the maximum pore size and is related to both the porosity and the fines content of the crushed aggregates (Côté & Konrad, 2003). From Table 4-7 it can be noted that all three blends show very low values of "a". The low fines content in blends, around 2%, can explain this trend. "a" value increases by decreasing the ratio of RG in the blends, varied from 0.110 KPa for MG20-100%RG to 0.235 KPa for MG20-100%FL. The parameter "n" of Fredlund and Xing's equation, which is referred to the pore-size distribution index (λ) (Côté & Konrad, 2003), controls the slope of the SWCC. From Table 4-7, MG20-100%RG presents the highest value of parameter "n", so the highest value of λ. Côté and Konrad

(2003) emphasize important influence of the porosity and S_{sf} on λ. The blends with higher proportion of RG have the lowest values of S_{sf} (S_{sf} of RG=1.68$\frac{m^2}{g}$) and the highest λ.

Aubertin et al (2003) illustrated that many factors can affect the water retention properties including shape, size, and distribution of pore size, mineralogy and surface activity of particles (Aubertin et al., 2003). Based on the results the blends with higher ratio of RG with lower value of "a", which is related to air entry value (ψ_a), and higher pore-size distribution index (λ) drain more easily than the reference material, MG20-100%FL.

4.5 Conclusion

A laboratory investigation was undertaken to characterize the recycled glass (RG) aggregate and blends with crushed limestone aggregate used as granular material in pavement structure regarding physical and hydraulic properties. In the first step, the separate sizes of RG and FL aggregate were assessed individually, and in the second step, the MG20 blends with RG were evaluated for use in the pavement base course. The physical properties results showed higher particle density and higher water absorption for crushed limestone than RG. RG aggregate showed negligible water absorption, which contributes to a better performance of aggregates against the development of absorbed water pressure during the freeze-thaw cycle in cold regions. Based on results, the difference between K values of RG and limestone aggregates is not significant. The measured K of mixed-size RG on the order of 1.94E-04 m/s suggest that RG can be used for many constructions and geotechnical engineering applications, including compacted fill, trench backfill, and base/subbase courses. Among the existing experimental methods to predict the K of aggregate, the methods of Hazen-Taylor, Kozeny-Carman, and Chapuis provide fair predictions for RG aggregate. The results of K tests on MG20 blends with RG suggest that RG can be replaced up to 100% of the fine fraction of MG20 (0-5mm) and contribute to an increase of K of base course aggregate. In terms of SWCC, RG tends to enhance the drainage capacity of base course materials, as lower ψ_a value and higher λ were found in comparison to limestone. For all the studied specimens, desaturation occurred below

low matric suction of 0.3 KPa. The model of Fredlund and Xing (1994) provides a good fit for the blends of RG. The properties of RG aggregate showed that this recycled material could be safely used in pavement base/subbases regarding hydraulic aspects. However, further research is in progress to study the behavior of blends of RG and MG20 used in the base/subbase layers.

CHAPTER 5

FEASIBLE USE OF RECYCLED GLASS AGGREGATE IN PAVEMENT UNBOUND GRANULAR MATERIALS

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5.1 Abstract

The suitability of recycled glass aggregate (RG) was evaluated for use as a pavement material in unbound base/subbase applications. Since the unbound aggregate plays a key role in the structural capacity, this paper covers the mechanical properties of base course aggregate with RG from laboratory testing. In this regard, RG with the range size of 0-5 mm replaced the fine proportion of base course material (MG20) based on volumetric method. The experimental study included compaction, Los Angeles (LA), Micro-Deval, and California bearing ratio (CBR) tests. All studied blends with 0 to 100% of RG in fine fraction of MG20 met the minimum requirements of unbound granular layers in the province of Quebec, based on the studied properties in the current study. Finally, a simple model was suggested for the RG blends to predict the resilient modulus values of studied materials based the CBR values.

5.2 Introduction

In recent years, fast growth of the world population has emphasized the waste generation. Remaining this kind of materials in the environment for a long time may lead to a waste-dumping crisis. Recycling waste into valuable engineering products can be a possible solution to this approaching crisis (Wilk et al., 2001). Among the various recycled materials, RG is of particular interest in the current study to be used as aggregate for unbound layers of pavements. Investigating the mechanical characteristics of the blends of RG is necessary since the unbound aggregate plays an important role in the structural capacity of the pavement system.

There are several studies that focused on the suitability of using RG in concrete mixtures (Corinaldesi et al., 2005; Meyer & Xi, 1999; Taha & Nounu, 2008) and in asphalt layers (Halstead, 1993; Lachance-Tremblay et al., 2017; Lachance-Tremblay et al., 2016; Landris & Lee, 2007; Meyer, 2001; Su & Chen, 2002; Taha & Nounu, 2008). Some researchers also have proposed using RG in other applications such as backfill material (Wartman et al., 2004a), and embankment fills (Grubb et al., 2006b; Halstead, 1993). However, few researches focus on applying RG in unbound materials (Arulrajah et al., 2013; CWC, 1998; FHWA, 1998; Ooi et al., 2008; Senadheera et al., 2005).

The previous study on glass shows that it can be added to natural aggregate while the blend would still possess the adequate resistance to abrasion and traffic loading (CWC, 1998). A study on RG in Hawaii reveals that RG, due to its large friction angle, has the potential to be used in foundation and ground improvement applications (Ooi et al., 2008). Shear strength test results also reveal that RG shows shear strength behavior similar to blends of sand and gravel with angular particles (Disfani et al., 2012). While RG is recognized to have some strength and drainage applications (Wartman et al., 2004a), its reuse potential is slowed down by the fact that there is inadequate knowledge regarding its engineering parameters. Furthermore, the processing equipment used to control the gradation of the crushed glass by different supplier affects the engineering properties (Wartman et al., 2004a). This study is an attempt to bridge these information gaps. The current paper aims to investigate the materials properties by compaction, Los Angeles (LA), Micro-Deval, and California bearing ratio (CBR) tests. Furthermore, an equation is proposed to connect the CBR values and the resilient modulus (M_r) values of materials, which is one of the required inputs for flexible pavement design.

Numerous studies have been conducted to evaluate the M_r of aggregate via CBR values (Ayres, 1997; Erlingsson, 2007; Green & Hall, 1975; Heukelom & Klomp, 1962; Hoff, 1999; Lister & Powell, 1987; Witczak et al., 1995). Among the existing models, the following models, Equation (5.1), (5.2), (5.3), and (5.4), which have been developed by Heukelom and Klomp (1962), Green and Hall (1975), Lister and Powell (1987) and Ayres (1997), respectively, are well-known among others.

$$M_r, MPa = 10.35CBR \tag{5.1}$$

$$M_r, MPa = 37.3CBR^{0.711} \tag{5.2}$$

$$M_r, MPa = 17.6CBR^{0.64} \tag{5.3}$$

$$M_r, MPa = 20.7CBR^{0.65} \tag{5.4}$$

The stiffness of unbound granular materials is influenced by several parameters, among which the stress level is very important (Erlingsson, 2007; Rahbar-Rastegar, 2017). However, this fact is not considered in the equations (5.1 to 5.4). Witczak et al (1995) and Erlingsson (2007) conducted some studies to consider the effect of the nonlinear resilient response of aggregate on the prediction model of Mr based on CBR values. However, RG blends were not included in the studied materials for the development of such relationships. Contrary to M_r test, the CBR test is a relatively easy and inexpensive test to characterize the bearing capacity of unbound granular materials in pavement structures (Yideti et al., 2014). Hence, proposing a relationship to predict the M_r based on CBR values, for RG blends, can be beneficial for engineering applications. In the following sections, the studied materials, the methodology to reach the above-mentioned objectives and the obtained results based on experimental study will be discussed and analysed.

5.3 Experimental study

The studied materials and applied methods to reach the objectives of the current study will be discussed in the following sections.

5.3.1 Materials

In the current research two types of materials were studied: recycled glass (RG) and crushed limestone aggregate. The RG aggregate, which is obtained from a sorting centre, was in size fraction of 0 to 5 mm. Crushed limestone in the range size of 0 to 20 mm, which is one of the prevailing aggregate for road construction, is used in this study as the reference material. The grain-size distribution of the reference material is under the requirements for MG20, the grading envelope specified for the base course according to local ministry of transportation (Figure 5-1). Six different specimens, which were blends of the limestone aggregate and RG, were used in this study.

In all cases, the replaced limestone aggregate was in the fraction size of 0 to 5 mm, which referred to as the fine fraction of limestone in this paper (FL). The replacement of FL with RG aggregates was performed using the volumetric method. The volumetric method ensures that the specific volume of reference material is replaced with the same volume and the same sizes of RG.

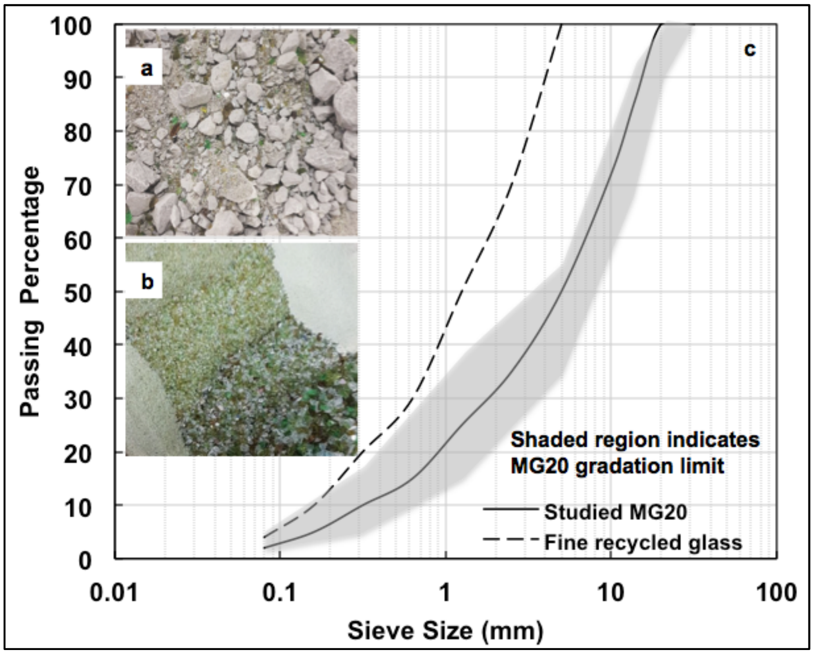

Figure 5-1(a) MG20 blends with RG (b) Mix size of RG (c)
Gradation curves for RG and MG20

Figure 5-2 presents the category of six specimens and the ratio of RG and limestone aggregate in each specimen. In all specimens, the replacement ratio varied between 25% to 100% of the fine fraction of MG20. The specimens consisted of MG20 with 100% limestone (MG20-100%FL), pure recycled glass (100%RG), and the MG20 blends with RG, which were named according to their composition (Figure 5-2).

5.3.2 Methods

In this section the laboratory tests to evaluate the related properties of materials are described. The experimental studies included compaction, Los Angeles (LA), Micro-Deval, and California bearing ratio (CBR) tests. These laboratory tests are described in the following paragraphs.

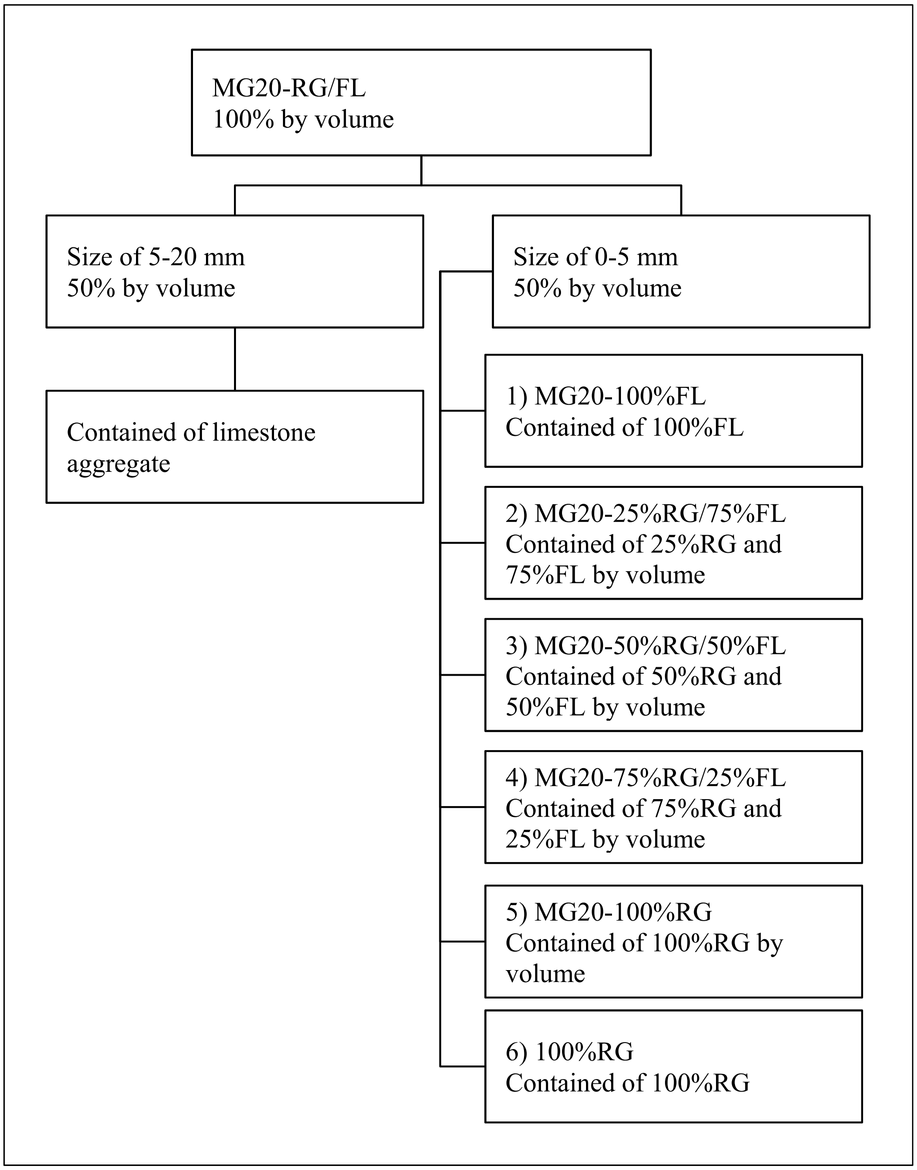

Figure 5-2 Size category of six specimens for experimental study

Modified Proctor compaction tests were performed on the blends of MG20 with RG aggregate and 100%RG. Based on the ASTM D1557-12 standard test method, each specimen was compacted using five layers, and each lift received 56 blows from 4.5 kg-hammer dropping 46 cm (ASTM, 2012a).

Los Angeles (LA) and Micro-Deval tests were performed to assess the durability and abrasion resistance of RG, limestone aggregate, and their blends. The LA abrasion test, based on ASTM C131 test method (ASTM, 2014a), is commonly used in highway engineering to assess the abrasion resistance of construction aggregate. In the current article, LA abrasion was measured for grade D, the range size of 2.5-5 mm. The Micro-Deval tests were conducted based on ASTM D7428 test method (ASTM, 2015b). Since the RG particle size was less than 5 mm, the fine fraction of MG20 was selected for Micro-Deval test for comparison the durability of RG and limestone aggregate. The Micro-Deval test is a measure of abrasion resistance and durability of aggregate resulting from a combination of actions including abrasion and grinding with steel balls in the presence of water (ASTM, 2015b).

The CBR tests were performed on the blends of MG20 with RG, as well as 100%RG aggregate using the ASTM D1883 test method (ASTM, 2016a). The CBR values, which represent the relative resistance of pavement materials to shear and penetration in comparison with a reference material, is an indirect measure of soil strength (Gonzalez, 2015; Yideti et al., 2014). CBR is also used to estimate the M_r of granular unbound materials. CBR test specimens were prepared at optimum moisture content based on modified compaction tests. Each specimen was soaked in water for four days with a surcharge mass of 4.5 kg after compaction. This condition simulated the confining effect of overlying pavement layers of a pavement (Arulrajah et al., 2013). The CBR value is a direct input parameter for certain design methods like empirical method. In more mechanistic design methods in which the elastic modulus is required, the CBR value is used to estimate the M_r from empirical relations between $\mathrm{M_r}$ and CBR (van Niekerk, 2002).

5.4 Results and discussions

This section presents the results and analyses of the experimental study in the four following sections. Table 5-1 presents some basic properties of the studied materials.

Table 5-1 Tested materials characterization

Properties	MG20-100% FL	MG20-25%RG/75%FL	MG20-50%RG/50%FL	MG20-75%RG/25%FL	MG20-100% RG	100% RG	Standard test method
Fine content (0-0.075 mm), %	2	2	1.9	1.9	1.9	4	ASTM (2017)
Sand content (0.075-4.75 mm), %	48	47.4	46.8	46.2	45.5	96	(ASTM, 2017)
Gravel content (4.75-75 mm), %	50	50.6	51.3	51.9	52.6	0	(ASTM, 2017)
RG Percentage corresponding to total volume, %	0	11.4	23.1	35.1	47.4	100	-
Coefficient of uniformity (Cu)	23.08	23.06	22.73	22.38	22.06	11.7	(ASTM, 2017)
Coefficient of curvature (Cc)	1.54	1.56	1.57	1.58	1.94	1.3	(ASTM, 2017)
USCS classification	SW	SW	SW	SW	SW	SW	(ASTM, 2017)
Specific gravity	2.761	2.727	2.694	2.660	2.626	2.491	(ASTM, 2014b)

5.4.1 Compaction

Figure 5-3 presents the compaction moisture-unit weight relationships for the blends of MG20 with RG. Zero air void curves, which illustrate the maximum dry unit weight as a function of moisture content for a fully saturated specimen, are also displayed for both RG and MG20 with the specific gravity of 2.491 and 2.761, respectively.

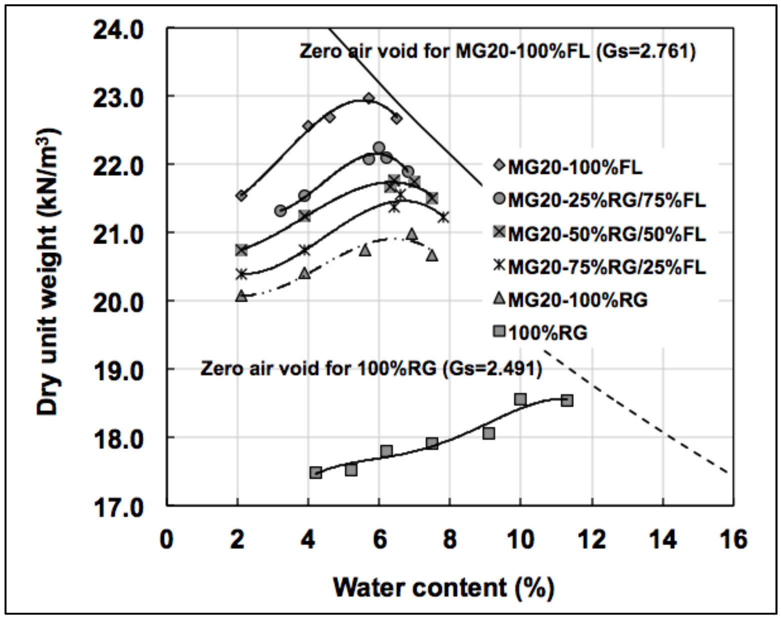

Figure 5-3 Modified Proctor results for MG20 blends with RG

The moisture-unit weight curves for MG20 blends showed the characteristic convex shape of natural aggregate (Wartman et al., 2004b). Hence, the blends with RG performed in a manner that is similar to natural aggregate. It can be seen that by decreasing RG amount, the moisture-unit weight curves switched up and to the left, relating to an increase in maximum dry unit weight (γ_{dMAX}) and a decrease of the optimum water content (W_{OPT}). It seems that the blends curves are mostly gather together, but the compaction curve of 100%RG is placed in the lower unit weight and higher water content range. As one would expect, the γ_{dMAX} values of blends were between those of their parent aggregate (MG20-100%FL and RG100%). The modified compaction results of MG20 blends with RG indicate that MG20/100%FL has the highest γ_{dMAX} while MG20-100%RG has the lowest value. In order to recognize the effect of RG on the compaction aptitude of MG20, the normalized dry density of specimens was calculated using Equation (5.5).

$$\rho_{dn} = \frac{\rho_{dMAX}}{P_{Recycled\ glass} \times \rho_{dRecycled\ glass} + P_{Limestone} * \rho_{dLimestone}} \quad (5.5)$$

Where ρ_{dn} is normalized maximum dry density of specimen (without unit), ρ_{dmax} is maximum dry density of blend ($\frac{gr}{cm^3}$), $P_{Recycled\ glass}$ is the proportion of RG in the blend, $\rho_{dRecycled\ glass}$ is particle density of RG, $P_{Limestone}$ is the proportion of limestone in the blend, and $\rho_{dLimestone}$ is particle density of limestone. This method helps to recognize the aptitude of compaction based on the unit weight of the solid particles. Table 5.2 shows the normalized maximum dry density for MG20-RG blends and the compaction results. It can be seen that the differences between ρ_{dn} of MG20-RG blends are not significant. Hence, the reduction of γ_{dMAX} of blends with increasing RG ratio can be explained based on the lower specific gravity of RG (G_s=2.491) than limestone (G_s=2.761). From the results presented in Table 5.2 it can be seen that the optimum water content of blends follows an upward trend with raising the ratio of RG in the fine proportion of MG20.

Table 5-2 Compaction results of studied materials

Material	$\gamma_{dMAX}, \frac{kN}{m^3}$	W_{OPT}	ρ_{dn}, **without unit**
MG20-100%FL	22.9	5.5	0.847
MG20-25%RG/75%FL	22.1	5.9	0.828
MG20-50%RG/50%FL	21.7	6.3	0.822
MG20-75%RG/25%FL	21.5	6.7	0.823
MG20-100%RG	20.9	6.4	0.812

The same trend was reported by Arulrajah (2014) when the fine RG was blended with waste rock (WR) and recycled concrete aggregate (RCA). γ_{dMAX} of blends decreased by increasing RG ratio. Grubb et al. (2006b) showed the reverse trend for the blends of crushed glass (CG) and dredged material (DM), which is a kind of marginal material, where the γ_{dMAX} increased with increasing CG ratio. The mentioned trend, however, was not observed when the crushed glass (CG) was blended with other dredged material like kaolinite (K) and quarry fines (QF) (Wartman et al., 2004b), which showed that the blends were denser than the individual materials. It can be seen that, as expected, γ_{dMAX} of limestone aggregate-RG blends depends on the kind of blended material and the distribution of particles in the blends.

The results of modified compaction tests on 100%RG ($\gamma_{\mathrm{dMAX}} = 18.5\ \frac{\mathrm{kN}}{\mathrm{m}^3}$) is in the range of indicated values by the previous researchers, $\gamma_{\mathrm{dMAX}} = 17.5 - 19\ \frac{\mathrm{kN}}{\mathrm{m}^3}$ (Arulrajah et al., 2014; Disfani et al., 2011a; Grubb et al., 2006b; Ooi et al., 2008; Wartman et al., 2004a; Wartman et al., 2004b). The difference between the reported values is due to the different particle size distribution of RG sources.

5.4.2 Durability tests

Figure 5-3 shows the LA abrasion values of RG and limestone aggregate. The durability of mineral aggregate decreased with the increase of the ratio of RG in the blends, as the LA abrasion loss followed an upward trend by increasing RG (a durability reduction around 17%). It is obvious that the limestone aggregate possessed the lower abrasion loss (23%), while RG aggregate hit the higher abrasion value (27%). Nevertheless, all studied specimens have the potential to be used as base course application as most of the road authorities over the world accept a maximum value of LA abrasion of 35% for base materials (Arulrajah et al., 2014).

The results of LA abrasion tests on RG presented in this study agree with the values found in previous studies including 24-25% indicated by Wartman et al. (2004a), 27-33% obtained by Ooi et al. (2008), and 24.8-25.4% by Disfani (2012). Measured LA abrasion values for RG by FHWA (1998) and CWC (1998) were reported 30-42% and 29.9-41.7%, respectively. The variation of LA abrasion results between the previous researchers seems to be associated with the different debris level of different specimens investigated (CWC, 1998).

Figure 5-5 illustrates the results of Micro-Deval tests on the blends of limestone and RG aggregate. As it can be seen, in the range of 0 to 5 mm, RG showed lower loss than limestone aggregate in the wet condition (RG aggregate with 10% versus limestone aggregate with 25% of abrasion). The blends of limestone and RG followed the downward trend by increasing RG percent. Based on a local standard of civil engineering (BNQ, 2014) all tested aggregate in this study possessed a Micro-Deval abrasion loss lower than the maximum threshold for roadwork base aggregate (30%). No study on Micro-Deval tests on RG blends was found in the literature.

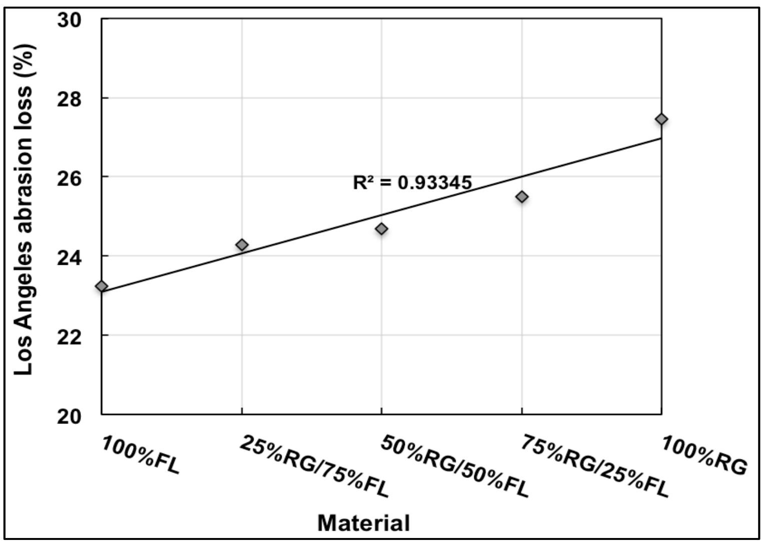

Figure 5-4 Results of LA abrasion tests on the blends of limestone and RG

Several authors have compared the results of LA abrasion test (dry condition of aggregate) and the Micro-Deval test (wet conditions of aggregate) (Mamlouk & Zaniewski, 2011). Since the procedure of LA test subjects the material to different degradation mechanisms, including abrasion, impact, and milling, it ends up being a test for evaluating the impact instead of abrasion (wearing and loss of angularity) resistance (Bessa et al., 2014; Lane et al., 2000). During Micro-Deval test, the contact of aggregate with water can simulate the field conditions better when compared with LA test in dry condition (Rogers, 1998; Yılmaz & Yılmaz, 2016).

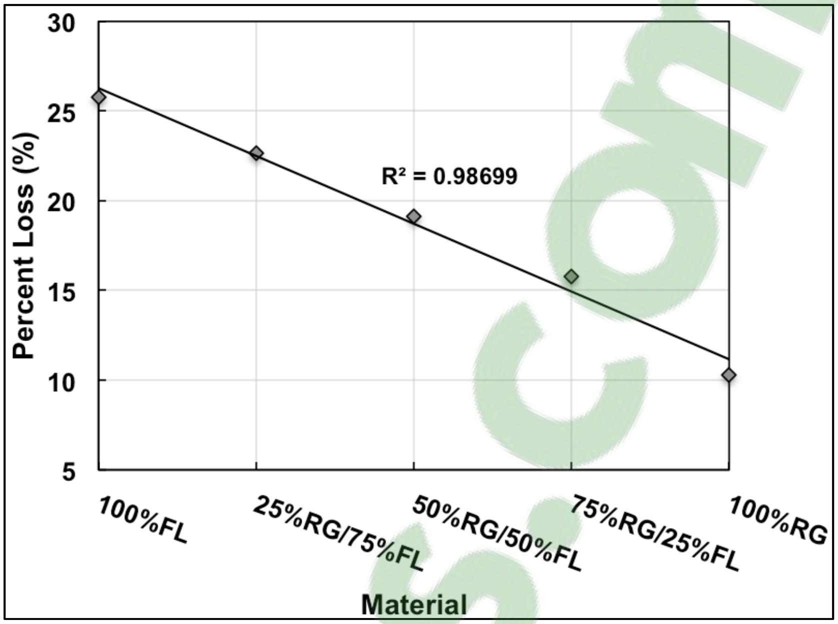

Figure 5-5 Results of micro-Deval tests on the blends of limestone and RG

It seems that in both dry and wet conditions, the blends of RG with limestone can meet the standard requirements for durability. In the dry conditions, the limestone aggregate had better abrasion resistance than RG. However, in a wet environment, more representative of in-situ conditions, adding RG to blends can improve the wet abrasion resistance. The combination of the Micro-Deval and Los Angeles tests seems to be beneficial in the conditions such as in the local area which experiences a varied climate, requiring the abrasion of aggregate in both wet and dry environments to be determined.

5.4.3 CBR testing

Figure 5-6 shows the variations of CBR values of blends with the changes in the RG percentage. The trend line drawn in Figure 5-6 is 2nd order polynomial. CBR values of blends did not change significantly with the increase of RG percentage from 0 to 25% in the blends.

By adding more RG to the blends and subsequent increase of RG from 25% to 100%, the CBR values decreased and MG20-100%RG hit the lowest value. Based on the results adding RG more than 25% to the MG20 can reduce its resistance against compressive forces. This decreasing trend in CBR values should be considered if the RG is used in the base course in the higher ratio of RG in the blends. Based on the previous research works, the CBR value of blends of RG with the maximum particle size of 4.75 mm with other materials, including CR, RCA, and WR with the maximum particle size of 20 mm, generally decreased with increasing RG ratio (Arulrajah et al., 2014; CWC, 1998). Arulrajah et al. (2013) explained that the CBR reduction with increasing RG ratio is due to its lower strength and lower quality compared to the reference aggregate.

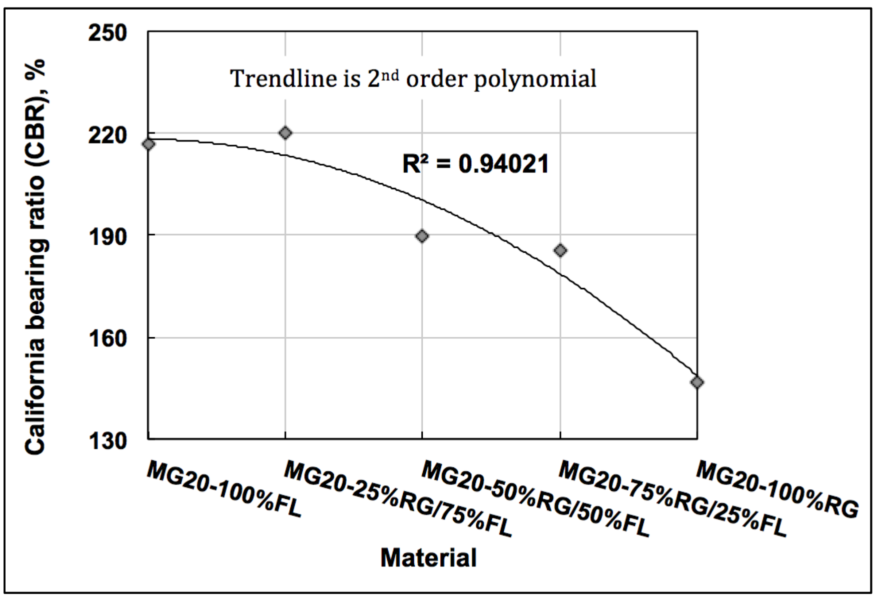

Figure 5-6 Results of CBR for the blends of limestone aggregate and RG in MG20

Based on the results, the CBR value of 47% was found for 100%RG, which is comparable with the values reported in previous research works. The previous researches reported the CBR values of 42-46% for RG and 181% for crushed rock (Ali et al., 2011). Ali et al. (2011) also obtained the CBR value of 44% for RG versus 211% for RCA. Ooi et al. (2008) investigated the characteristics of three recycled materials, including RG, RCA, and recycled asphalt pavement (RAP). The results of their study showed that the CBR value of RG (75-80%) falls between those of RAP and RCA, more than RAP and less than RCA.

National Cooperative Highway Research Program (NCHRP) (ARA, 2004) indicates the minimum CBR values of 100% and 80% for the base and subbase course materials, respectively. Based on the results, all the blends met the requirement for usage as a base/subbase layer material. However, 100%RG, with the CBR value of 47% needs to be blended with other materials to increase strength and stiffness and to satisfy the road base/subbase requirements.

5.4.4 Predicting Mr value based on CBR value

This study is performed on the base course aggregate, which experiences the stress regime due to wheel load moving on the surface of pavement structure. Here, one decision needs to be made about the stress level at which the CBR should be compared to M_r values, as the M_r is stress dependent (Lekarp et al., 2000a). At 10 to 15 cm depth under surface layer, the approximate induced vertical stress under the 8-ton axle load (ARA, 2004) with a tire pressure of 600 KPa is of the order of 400 KPa (Ullidtz, 1987). The horizontal stresses are approximately one-third of the vertical value (Erlingsson, 2007; Erlingsson & Magnusdottir, 2004). The mean normal stress value becomes therefore approximately 230 KPa. This value is considered as the reference mean normal stress level. To compare the capability of the models (5.1) trough (5.4) to predict the M_r of studied materials, the results of M_r corresponding to the mean normal stress of 230 KPa are presented in Figure 5-7. Table 5-3 presents the results of M_r test on the blends of RG from another study by the same authors (Amlashi et al. 2018).

The four equations described in Figure 5-7, present very different results. All equations lead to overestimations of the $\mathrm{M_r}$ values. Equation (5.3), which is considered in the current article to predict $\mathrm{M_r}$, gives better agreement with the measurements than others.

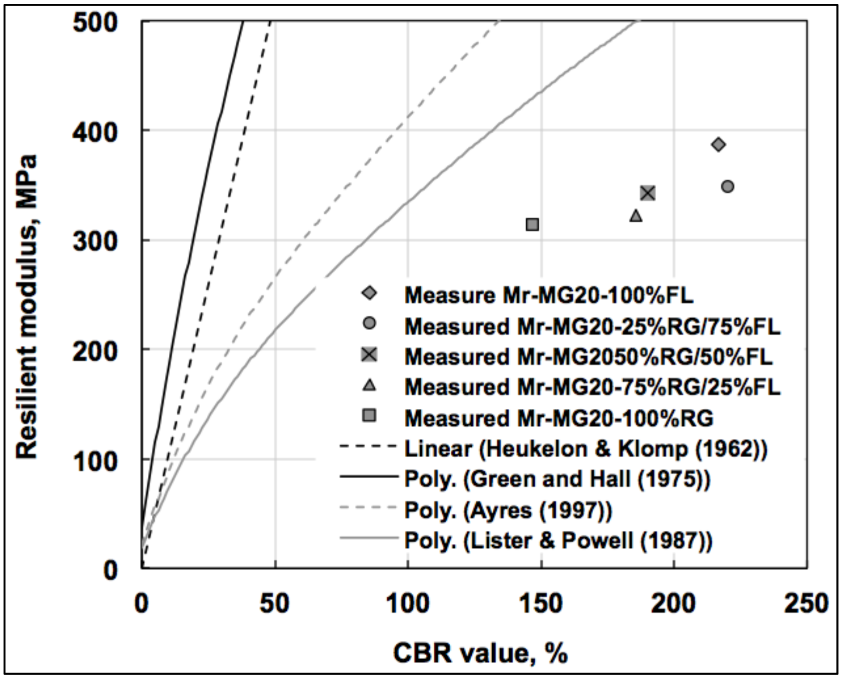

Figure 5-7 Predicted M_r as a function of CBR values according to the Equations (5.1-5.4) and measured M_r of MG20-RG blends

To reach a relationship between M_r, CBR, and stress level, $k-\theta$ model is applied in the current research. The simplicity of this model has made it highly useful and accepted for analysis of stress dependency of $M_r(MPa)$ (Hicks & Monismith, 1971; Lekarp et al., 2000b; Schwartz, 2002):

$$M_r = k_1\theta^{k_2} = k_1(\frac{3P}{P_a})^{k_2} \tag{5.6}$$

$$P = \frac{1}{3}(\sigma_1 + 2\sigma_3) \tag{5.7}$$

Table 5-3 M_r results based on laboratory measurement by the same authors (Amlashi et al., 2018)

Step No.	**Confining Stress (σ_3), KPa**	**Deviatoric Stress (σ_d), KPa**	**Mean Stress (P), KPa**	**M_r values, MPa**				
				MG20-100%FL	**MG20-25%RG/75%FL**	**MG20-50%RG/50%FL**	**MG20-75%RG/25%FL**	**MG20-100%RG**
1	21	21	28	116	109	107	99	100
2	21	41	35	121	116	115	107	106
3	21	62	42	127	124	125	116	115
4	35	35	47	142	133	134	126	124
5	35	69	58	153	149	151	141	140
6	35	103	69	169	163	164	153	154
7	69	69	92	204	195	200	187	185
8	69	138	115	239	223	223	210	214
9	69	207	138	266	247	246	228	235
10	103	69	126	243	231	234	216	218
11	103	103	137	264	247	248	231	236
12	103	207	172	318	288	286	268	270
13	138	103	172	298	274	274	265	264
14	138	138	184	326	291	291	280	279
15	138	276	230	387	349	343	322	314

Where $k_1 (MPa)$ and k_2 are regression coefficients, P is the mean normal stress, P_a is the atmospheric pressure, $P_a = 100kPa$, and σ_1 and σ_3 are the principal stresses in KPa, respectively. Table 5-4 presents the k_1 and k_2 values according to Equation (5.6) for all specimens based on the results of laboratory measured M_r (Table 5-3).

As can be seen in Table 5-4, k_1 values lie in the range of 104 MPa and 116 MPa, and k_2 values lie mostly in the range of 0.558-0.588. The differences of k_2 values from the mean value are lower than those of k_1. Therefore, the average value of $k_2 = 0.57$ can approximately represent the response of all specimens. Assuming $k_2 = 0.57$, k_1 can be back-calculated based on the Equations (5.3) and (5.6) using $P = 230$ KPa as:

$$k_1^{\circ} = \frac{M_r}{(\frac{3P}{P_a})^{k_2}} = \frac{17.6CBR^{0.64}}{(\frac{3 \times 230}{100})^{0.57}} = 5.85CBR^{0.64} \tag{5.8}$$

The stress dependency of the M_r of MG20 blends with RG aggregate can be estimated by combining Equations (5.6) and (5.8) as:

$$M_r = 5.85CBR^{0.64}(\frac{3P}{P_a})^{0.57} \tag{5.9}$$

Table 5-4 CBR value, k_1 and k_2 values from M_r testing, the calculated k_1° value if $k_2 = 0.57$ and the % difference between the measured and predicted M_r at P=230 KPa ($\Delta, \%$)

Material	**CBR, %**	$\mathbf{k_1}, \boldsymbol{MPa}$	$\mathbf{k_2}$	$\mathbf{k_1^{\circ}}, \boldsymbol{MPa}$	$\Delta, \%$
MG20-100%FL	217	116	0.588	182.92	29.6
MG20-25%RG/75%FL	220	112.1	0.559	184.85	37.2
MG20-50%RG/50%FL	190	112.3	0.558	168.12	32.2
MG20-75%RG/25%FL	186	104.2	0.568	165.73	35.4
MG20-100%RG	147	104.0	0.571	142.58	26.8

The difference between measured and predicted M_r values at P=230 KPa are also presented in Table 5-4. It can be seen that the modified equation overestimates the M_r values for RG blends up to 37.2%. It can be explained by the point that the RG blends were not included in the studied materials for the development of the existing empirical relationships to estimate M_r based on CBR. Based on a simple data analysis, a modifying coefficient of 0.635 was obtained and applied to the suggested equation to estimate M_r on a safer side. By applying the modifying coefficient, the predicted M_r values became closer to the measured values. Therefore, the stress dependency of the M_r of RG blends can now be estimated by Equation (5.10) as:

$$M_r = 3.71CBR^{0.64}(\frac{3P}{P_a})^{0.57} \tag{5.10}$$

The proposed model can predict the M_r values of various RG blends based on the related CBR values, for different mean stress levels. The M_r versus a wide range of mean normal stress (28-230 KPa) for the studied blends is presented in Figure 5-8(a) where both the measured and predicted M_r values based on Equation (5.10) are given. As can be seen from Figure 5-8(a), the differences are not significant. To verify the proposed model predictive capacity, the measured M_r values of MG20-10%RG based on other study by the same authors and predicted M_r based on Equation (5.10) are compared in Figure 5-8(b). A good agreement was found between measured and predicted values with the use of the proposed model. Therefore, by knowing the CBR value of MG20-RG blends the M_r values can be estimated under different mean normal stress levels. It means that for different RG ratios, the M_r value can be estimated using the suggested model if a simple CBR test is conducted.

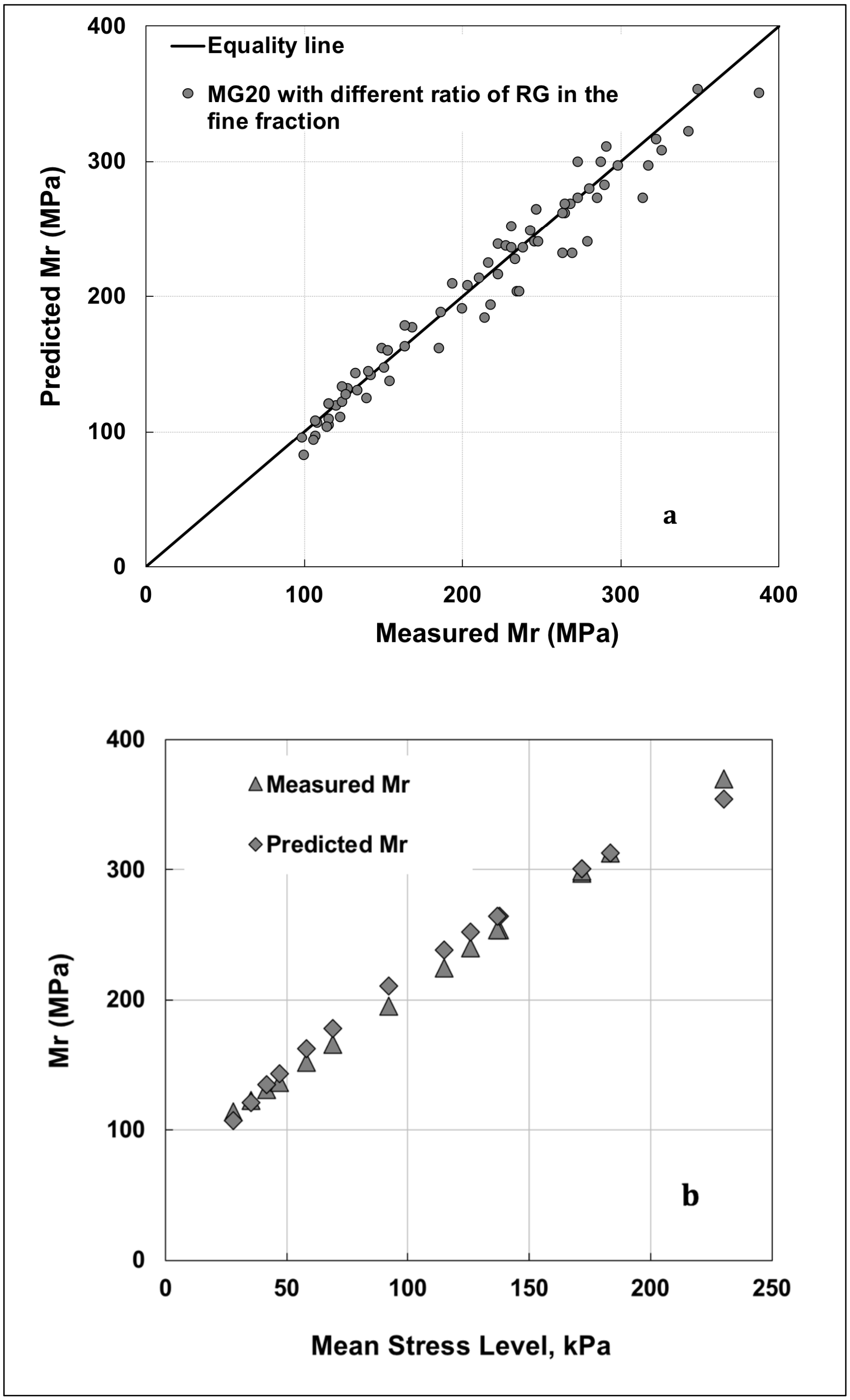

Figure 5-8 (a) Predicted versus measured graph of Mr for the suggested equation (b) M_r value versus mean stress level for MG20-10%RG/90%FL based on measured and predicted values

5.5 Conclusion

A detailed laboratory investigation was undertaken to examine the effect of recycled glass (RG) on the mechanical behaviour of RG blends. Crushed limestone was considered as the reference material, which is one of the common aggregate of granular materials used in pavement base/subbase for roadwork. The size range of limestone aggregate was varied from 0 to 20 mm, based on MG20 gradation curve, and RG was in the range of 0 to 5 mm. To prepare the specimens, the fine fraction of limestone aggregate (0-5 mm) was replaced by RG for different ratios, using a volumetric method. The current study aimed to investigate the feasibility of using RG as aggregate in unbound materials of pavement structures, from a mechanical property point view. In this regard, three common laboratory tests were performed on various RG blends, including modified Proctor compaction, durability (LA abrasion and Micro-Deval tests), and CBR tests. Also, a simple model was suggested for predicting the M_r of the RG blends based the results of CBR tests.

Based on the results of modified Proctor compaction tests, γ_{dMAX} decreases gently by increasing the RG ratio and, $\mathrm{W_{OPT}}$ followed the opposite trend. Based on LA abrasion and Micro-Deval tests results, the RG blends have the potential of being used in base course application. Adding RG to the blends can improve the durability of the mix in wet condition, which is more similar to the field condition. However, the durability of blends decreased in the dry condition by increasing RG ratio but remained in the acceptable ranges. It seems the combination of Micro-Deval and LA abrasion tests are beneficial to capture a better view of RG blends abrasion resistance.

CBR tests indicate lower values for the blends with higher amount of RG, however, all the studied blends meet the CBR requirement for usage as a base/subbase layer material. It is also concluded that for the studied materials a simple prediction equation can be used to estimate $\mathrm{M_r}$ based on CBR values. The prediction model by Lister and Powell (1987) for the mean stress value of 230 KPa gives the best results among other equations presented here (Lister & Powell, 1987). It is further concluded that if the $\mathrm{k} - \theta$ model is considered for evaluating the stress dependency of $\mathrm{M_r}$ and using $k_2 = 0.57$, then $\mathrm{k_1}$ can be achieved by a simple back calculation based on CBR value. The suggested equation seems to give a satisfactory estimation of $\mathrm{M_r}$ for the range of mean stress level between 28 – 230 KPa. This equation can help to estimate the M_r values of various RG blends, under the range of mean stress levels, by knowing the related CBR value.

The current research suggests some valuable information about the mechanical characteristics of RG in roadwork applications based on the typical road authority requirements. Considering CBR results, all RG ratios (0-100%) meet the minimum requirements for the blends of unbound granular base/subbase layers. From mechanical point of view, RG can be used in different ratio in the base or subbase layer, depending on the roadwork applications and the stress distribution through the structural layers. However, it is essential to evaluate other engineering aspects including the thermal, hydraulic, and deformation behaviours of blends to define an acceptable ratio of RG in the blends.

CHAPTER 6

RESILIENT MODULUS OF PAVEMENT UNBOUND GRANULAR MATERIALS CONTAINING RECYCLED GLASS AGGREGATE

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6.1 Abstract

With the increased knowledge of sustainable pavement construction, recycled materials more and more are being used in roadwork applications, especially as base materials. Among various recycled materials, recycled glass aggregate is of the special attraction in the present study. The main goal of this investigation is evaluating the behavior of base course containing recycled glass using resilient modulus (M_r) from laboratory testing. In this regard, recycled glass (RG) is replaced the same range size of the local base course material (MG20) based on volumetric method. The studied RG aggregate was in the range size of 0-5 mm. The results revealed that as RG content increased, M_r values of blends decreased. Furthermore, the shear strength of blends followed the similar trend as it decreases by RG contents. Finally, based on the experimental observation a model was proposed to interpret the effects of RG on the resilient modulus values of blends. Conclusively, using RG up to 25% of MG20 may change the growing trend of

environmental problems, in a green way, without significant effects on the mechanical behavior.

6.2 Introduction

For the last two decades, recycled materials have been used in pavement structures, but their response and behavior under repeated traffic loading have not been adequately characterized. Among the various recycled materials available, recycled glass is of particular interest in the current study. The limited knowledge on the deformation behavior of recycled glass when submitted to repeated loads, limits the potential of reuse in roadwork applications.

This study focuses on using recycled glass as aggregate for the unbound layers of pavement, such as base and subbase. The unbound layers are working as a platform for the overlaying bounded layers (Mohapatra & Kumari, 2017). These layers also play an important role in the distribution of the traffic loads through underlying layers, and consequently, are essential to ensure the adequate overall performance of the pavement system (Lekarp et al., 2000b). Therefore, understanding the response of base course aggregates with recycled glass under traffic loading is critical. The deformation responses of granular materials under repeated loads are described by a resilient and a permanent strain response.

Repeated load triaxial testing provides fundamental information for analysis and design of pavements. It is used to evaluate the resilient modulus and permanent deformation behavior. The resilient modulus, M_r, is defined as the ratio of the applied cyclic deviatoric stress to the recoverable axial strain after a limited number of load cycles (FHWA, 2006). This parameter is important for the load-carrying ability of the pavement (Lekarp et al., 2000b). Permanent deformation is measured through triaxial repeated load tests for a high number of load cycles (FHWA, 2006). Permanent strain response characterizes the long-term performance of the pavement and the rutting phenomenon (Lekarp et al., 2000b; Rahbar-Rastegar et al., 2017).

Previous studies noted that there are some aspects which influence the M_r such as stress level, aggregate type, particle shape, and moisture content (Bilodeau & Doré, 2012; Craciun & Lo, 2009). It is admitted that, at higher degrees of saturation, a significant decrease of M_r of granular materials is noticed (Heydinger et al., 1996). Bilodeau et al. (Bilodeau et al., 2016) have emphasized the effects of grain size distribution and aggregate source properties such as frictional properties on the M_r and provided a model to describe their effects on the M_r of unbound granular materials. For a given gradation, crushed materials with high angular rough-shaped aggregates provide better resilient behavior when compared to uncrushed materials (Tarmuzi et al., 2015). According to Lekarp et al. (2000a), M_r increases considerably with confining stress, but only slightly with deviatoric stress.

Based on the literature, several parameters affect permanent strain development in unbound granular assemblies including the number of load repetitions, confining pressure, stress levels, moisture content, gradation, and aggregate types (Lekarp et al., 2000b). Among them, the importance of applied stress level and the number of load repetitions has been highlighted in the literature (Lekarp et al., 2000b). The permanent deformation response under repeated loading is controlled by the magnitude of repeated stress for the constant condition of moisture and density. As a concept, when the amplitude of the repeated stresses is increased, the permanent deformation increases (Alexandria, 2013; Werkmeister, 2003). However, the confinement stress affects permanent strain inversely (Cerni et al., 2012). The number of loads also influences the long-term behavior of granular materials as continuous increase of permanent strain is typically observed with the number of load cycles due to the elasto-plastic response (Craciun & Lo, 2009). Angular and rough textured aggregate demonstrate better resistance to permanent deformation under wheel loading as they lead into better particles interlock in comparison with rounded particles (Craciun & Lo, 2009; Mishra & Tutumluer, 2012). Lekarp et al. (2000b) mentioned that the effect of particle size distribution on permanent deformation of granular materials is a disputed subject among the researchers and there are different views about it.

The results of the M_r tests of glass cullet mixed with the crushed rock by Clean Washington Center (CWC) (1998) indicate that all specimens, even with up to 50% of glass cullet, generally exhibit appropriate resilient modulus for pavement applications. Wartman et al. (2004b) investigated the strength characteristics of crushed glass-Kaolin blends. The results of their research proved that the frictional strength of the soils increases with glass content, which allow these kinds of blends to be considered as interesting candidates for structural fill, backfill and embankment construction (Wartman et al., 2004b). Senadheera et al. (2005) provided the results of M_r of glass cullet and caliche, which is a weathered limestone and used as a subbase material in many parts of Texas. They demonstrated that M_r, and axial permanent strain, of caliche-glass cullet blend, increases with increasing glass content (Senadheera et al., 2005).

Ali et al. (Ali et al., 2011) evaluated the applicability of recycled glass blended with crushed rock for usage in pavement structures. The results of M_r test showed that permanent deformation increases with an increase of glass content, but the trend was not consistent due to the variation of water content between the specimens (Ali et al., 2011). However, according to Ali et al. (2011), the M_r of the mix is not sensitive to changes in either moisture or recycled glass content. Arulrajah et al. (2014) who studied the blends of recycled glass (RG) with recycled concrete aggregates (RCA) and waste rock (WR) showed that for RG/RCA blends, the permanent strain does not vary with moisture content and RG content. However, the M_r was found to decrease when recycled glass content and moisture content increases (Arulrajah et al., 2014). For RG/WR blends, a higher content of glass additive generally leads to higher permanent strain as the RG has lower stiffness and durability than WR, but inconsistent trends were observed due to water content variations (Arulrajah et al., 2014).

The research works so far on the resilient behavior of recycled glass are limited to the blends of recycled glass with some specific materials including caliche, waste rock, recycled concrete aggregates, and crushed rock, across the U.S and Australia. The recycled glass used in the previous research works had different gradations and was produced with different processing equipment than the recycled glass used in the current study; this is likely to cause a variety of engineering properties of blends. Furthermore, for the research project presented in this paper, the reference material is crushed limestone with a grain-size distribution by the requirements for MG20. MG20 gradation envelope is specified for the base course according to Ministry of Transport, Urban Mobility and Electrification of Transportation of Quebec (MTMDET) (Figure 6-1).

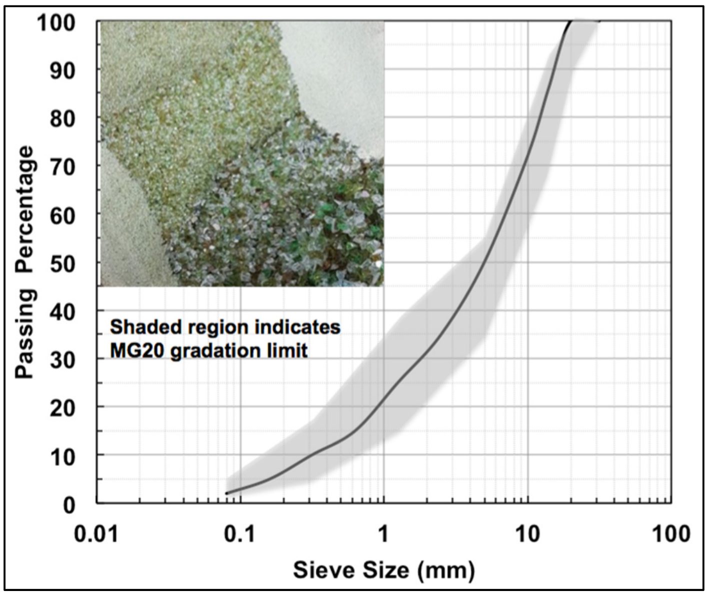

Figure 6-1 Gradation curve for MG20

Another interesting difference between the present work with previous researchers is the volumetric replacement method for combining recycled glass with limestone aggregate. The previous studies in this area considered weight percentage as a criterion, for using recycled glass for aggregates substitution. They replaced the aggregates with the same weight of recycled glass. The use of such method caused the volume of glass used in the mixture to become larger than the volume of the replaced proportion of aggregate because of different specific gravities. However, the volumetric method ensures that the specific volume of reference material is replaced with the same volume of recycled glass. Furthermore, as part of this replacement procedure, the aggregates are replaced by the same sizes of recycled glass. Therefore, the gradation of the granular reference material remains the same for all the specimens tested.

The lack of knowledge on the stiffness and strength characteristics, as well as performance under repeated loads, of recycled glass blends, limits the use of such blends in pavement structures. The current research aims to investigate the resilient and permanent deformation of blends of recycled glass and limestone using cyclic triaxial tests.

6.3 Experimental Study

The materials and methods used in this study will be discussed in the following sections.

6.3.1 Materials

In the current research two types of materials are studied: recycled glass (RG) and crushed limestone aggregate. Recycled glass aggregate, which is obtained from a sorting center, is in the size range of 0-5 mm. Crushed limestone aggregate, used in this study as the reference material, is one of the prevailing aggregates for road construction. The present work considered the limestone granular material in the range size of 0-20 mm. Five different specimens, the mix of limestone aggregate and recycled glass, were used in this study. In all cases, the replaced limestone aggregate was in the range of 0-5 mm, which is referred as the fine fraction of limestone in this study. The replacement of limestone aggregate with recycled glass aggregate was performed using a method based on volume instead of weight. It means that, for the fine fraction of the reference MG20, the same volume of limestone aggregate was replaced by RG.

In all specimens, the replacement ratio varied between 25% and 100% of the fine fraction of MG20. The five aforementioned specimens, which are presented in Table 6-1, are named according to their composition. For example, the MG20 made of 100% limestone is named MG20-100FL, and the mix that includes 50% of fine recycled glass and 50% of fine limestone aggregate (with the coarse part being the only limestone) is named MG20-50%RG/50%FL.

Table 6-1 Tested materials characterization

Properties	**MG20-100% FL**	**MG20-25%RG /75%FL**	**MG20-50%RG /50%FL**	**MG20-75%RG /25%FL**	**MG20-100%RG**	**RG 100%**	**Standard test method**
Fine content (0-0.075 mm), %	2.0	2.0	1.9	1.9	1.9	4	(ASTM, 2011)
Sand content (0.075-4.75 mm),%	48.0	47.4	46.8	46.2	45.5	96	(ASTM, 2011)
Gravel content (4.75-75 mm), %	50.0	50.6	51.3	51.9	52.6	0	(ASTM, 2011)
RG Percentage corresponding to total volume, %	0.0	11.4	23.1	35.1	47.4	100	
Cu	23.08	23.06	22.73	22.38	22.06	11.7	(ASTM, 2011)
Cc	1.54	1.56	1.57	1.58	1.94	1.3	(ASTM, 2011)
USCS classification	SW	SW	SW	SW	SW	SW	(ASTM, 2011)
$\rho_{dmax}{}^{a}$, kg/m3	2339	2258	2213	2189	2131	1886	(ASTM, 2012a)
$w_{opt}{}^{b}$, %	5.5	5.9	6.3	6.7	6.4	10.8	(ASTM, 2012a)
$\rho_{s}{}^{c}$, kg/m3	2761	2727	2694	2660	2626	2491	(ASTM, 2014b)
Flow coefficient (<2mm)[d]	149	-	-	-	-	104	(MTMDET, 2015)
Flow coefficient (<1.25mm)[d]	115	-	-	-	-	82	(MTMDET, 2015)
Flow coefficient (<0.63mm)[d]	94	-	-	-	-	80	(MTMDET, 2015)

[a] ρ_{dmax}: Max dry density-modified Proctor
[b] w_{opt}: Optimum water content
[c] ρ_s: Particle density
[d] Performed on three distinct granular fractions: $1.25\text{mm} < d < 2\text{mm}$, $0.63\text{mm} < d < 1.25\text{mm}$, and $0.315\text{mm} < d < 0.63\text{mm}$.

6.3.2 Methods

The sieve analysis and modified Proctor test were conducted before M_r test. Table 6-1 presents the properties of studied aggregates.

In this research, the M_r tests were conducted based on AASHTO T307-99 (AASHTO, 2003). Each specimen was compacted to its maximum dry density (ρ_{dmax}), on the dry side of the optimum water content (w_{opt}) (approximately 1% lower than w_{opt}). Vibratory compaction was selected because it is acknowledged as less damaging to materials than other compaction techniques such as modified Proctor (Bilodeau et al., 2010). Therefore, the specimens maintained the same shape without be significantly broken. The specimens were compacted with a vibratory hammer in six layers in molds of 150 mm in diameter and 350 mm in height, but to heights of 300 ± 1 mm. As proposed in AASHTO T307-99 (AASHTO, 2003), each sub-layer was compacted to the target thickness of 50 mm using the appropriate amount of wet material to achieve the maximum dry density. The specimens were unmoulded for installation within the triaxial cell (Figure 6-2(a) and (b)). Two latex membranes were installed, on top of another, to ensure adequate protection from punching and tearing due to sharp angular glass particles in the mixes. The membrane was put in the cylindrical container with the diameter bigger than the diameter of the specimen (Figure 6-2(c)) and vacuumed to be attached to the inner wall of container. Keeping the vacuum in the cylindrical container, the first membrane was placed on the sample (Figure 6-2(d)). The same method was followed for installing the second membrane on the top of the first membrane (Figure 6-2(e)). Afterward the sample is ready to be installed in the triaxial test (Figure 6-2(f)).

Two linear variable differential transducers (LVDT) were fixed at 180° apart on the piston rod, outside the test chamber, to measure the axial deformation of specimens. After subjecting the specimens to 1000 load cycles, the M_r tests were performed for the 15 stress steps, as presented in Table 6-2. The load was applied for 0.1 s, followed by a 0.9 s rest period.

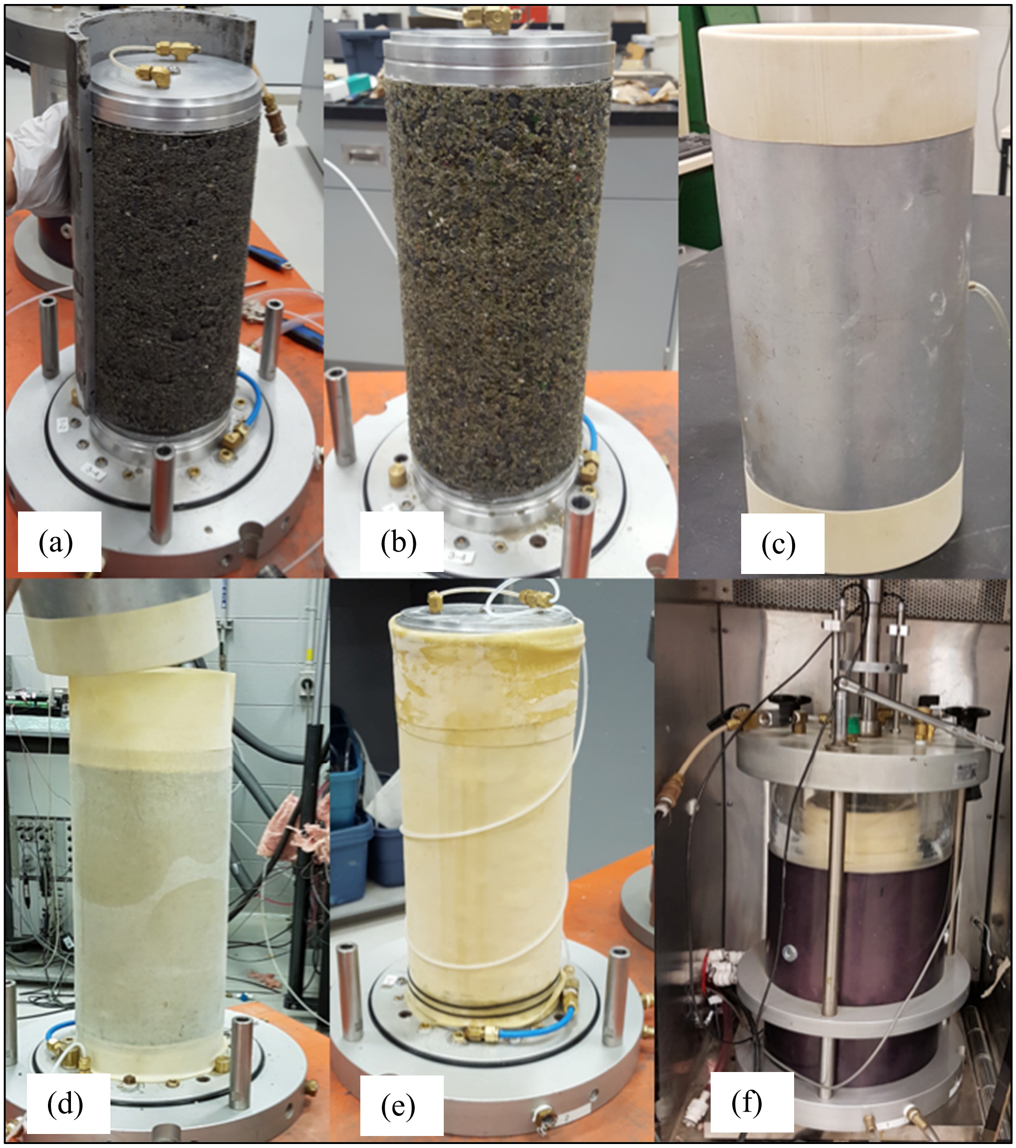

Figure 6-2 (a) Removing split mould after compacting the specimen (b) Unmoulded specimen (c) Accessory for placing the latex membranes on the specimen (d) Specimen with first membrane and installing the second membrane (e) Specimen ready for test (f) Specimen installation in the triaxial cell

6.4 Results and Discussion

The results obtained from the M_r tests performed on the studied specimens are presented in three following sections, and discussions on the results are presented as well in these sections.

Table 6-2 Stress states applied during resilient modulus tests

Step No.	**Bulk Stress (θ), kPa**	**Confining Stress (σ_3), kPa**	**Deviatoric Stress (σ_d), kPa**	**Cyclic Stress, kPa**	**Contact Stress, kPa ($0.1\sigma_d$)**	**No. of Load Cycles**
0	414	103	103	93	10.3	1000
1	83	21	21	19	2.1	100
2	104	21	41	37	4.1	100
3	124	21	62	56	6.2	100
4	138	35	35	31	3.5	100
5	172	35	69	62	6.9	100
6	207	35	103	93	10.3	100
7	276	69	69	62	6.9	100
8	345	69	138	124	13.8	100
9	414	69	207	186	20.7	100
10	379	103	69	62	6.9	100
11	414	103	103	93	10.3	100
12	517	103	207	186	20.7	100
13	517	138	103	93	10.3	100
14	552	138	138	124	13.8	100
15	690	138	276	248	27.6	100

6.4.1 Resilient Modulus Behavior of RG Blends

The obtained resilient modulus results for different stress steps on the specimens are illustrated in Figure 6-3. From Figure 6-3, it can be concluded that M_r of blends decreased when RG content increased. In the first stress steps (steps 1 through 7, corresponding to the bulk stresses of 82 KPa and 276 KPa, respectively), the effect of RG contents on the M_r of MG20 is less significant. It means that in the lower level of traffic stress, the base or subbase layers of pavement containing RG have similar stiffness to the standard unbound granular materials. Under higher stress levels (steps 8 through 15, corresponding to bulk stresses of 345 KPa and 690 KPa, respectively), the recycled glass addition causes a 10% to 19% decrease of the $M_r$value of the mix. This decreasing trend in modulus should be considered if the recycled glass is used in the base course under higher stress level from the traffic.

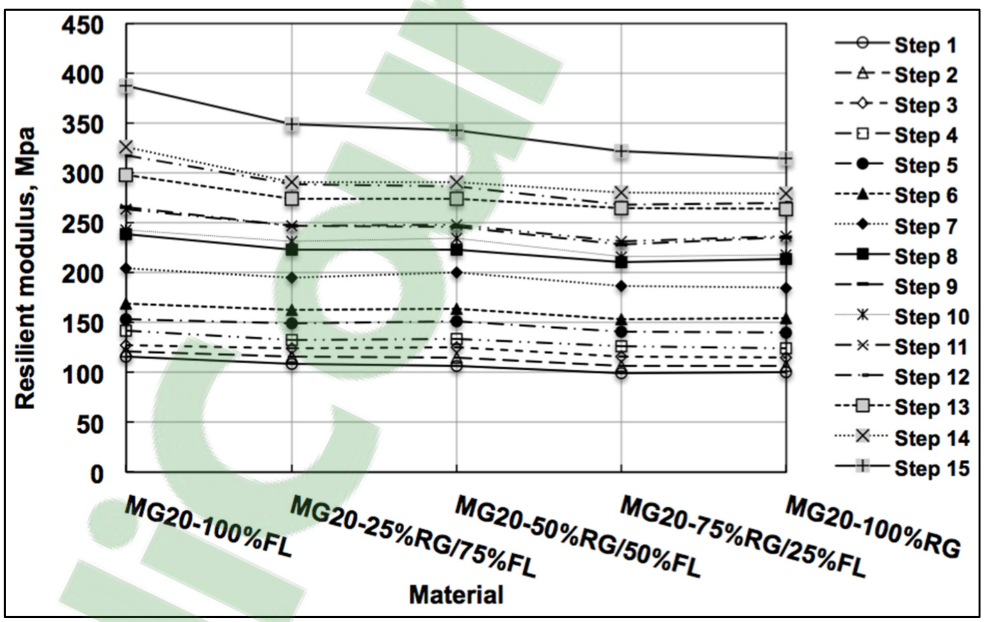

Figure 6-3 Resilient modulus of base course aggregates and recycled glass mix

As mentioned before, the aggregate shape is an important factor controlling M_r, as the angular rough-shaped aggregates provide better resilient behavior (Tarmuzi et al., 2015).

According to the flow coefficient shown in Table 6-1, limestone aggregate has a higher flow coefficient values than recycled glass. It is accepted that the higher flow coefficient leads to the higher angularity or rougher surfaces of particles or the combination thereof (MTMDET, 2015). Therefore, the limestone aggregate spreads load better than recycled glass because of better interlock among particles. The lower angularity or roughness of RG led to a reduction of the interlock of fine aggregates in the mix and caused an increase of the recoverable deformation for the same stress level, by increasing RG percentage in the mix.

Clean Washington Center (CWC, 1998) and Arulrajah et al. (Arulrajah et al., 2014) performed Mr tests on the mix of recycled glass (RG) and crushed rock and recycled concrete aggregates (RCA). The same trend was reported for RG/CR and RG/RCA in which adding recycled glass decreases the M_r of blends. Senadheera et al. (2005) illustrated a reversed trend for blends of recycled glass and caliche in which the higher contents of RG increased M_r of blends. It can be concluded that in blends, the relative strength of both RG and reference aggregates can affect the response of materials.

The resilient modulus of unbound materials is one of the required inputs for flexible pavement design. Hence, proposing a model that can predict the resilient modulus values of RG blends, based on the percentage of RG in the blends is likely to be practical in roadwork engineering design. According to the results presented in Figure 6-3 the effect of RG is sensitive to stress. Based on the previous literature review and our results, the stress level is a key factor contributing to the resilient modulus of unbound granular materials (Lekarp et al., 2000a; Wolfe, 2011).

As five different ratios of RG were tested, it is proposed to model the changes of $\mathrm{M_r}$ with changes of RG with a linear relationship, which is expressed as:

$$M_r(MPa) = A \times \%RG + B \tag{6.1}$$

Where, %RG is the percentage, by volume, of recycled glass in the fine fraction of MG20; A and B are coefficients that represent the slope (A) and the intercept (B) values of the $\mathrm{M_r}$

versus %RG relationship, and they were estimated in each step of resilient modulus test. Based on Figure 6-3, the intercepts of $\mathrm{M_r}$ charts corresponding to each step increase by increasing the level of bulk stress (corresponding to each step of $\mathrm{M_r}$ testing). Therefore, identifying a linear relationship between B and bulk stress (θ) is suggested. Figure 6-4 (a) presents the relationship between B and θ values. Hence, based on the linear best fit of data, the following equation is proposed:

$$B = 0.43 \times \theta + 79.06 \tag{6.2}$$

Where θ is bulk stress, in KPa, which is defined in equation 6.3.

$$\theta = \sigma_d + 3\sigma_3 \tag{6.3}$$

Where σ_d and σ_3 are the deviatoric and confining stress in KPa, respectively.

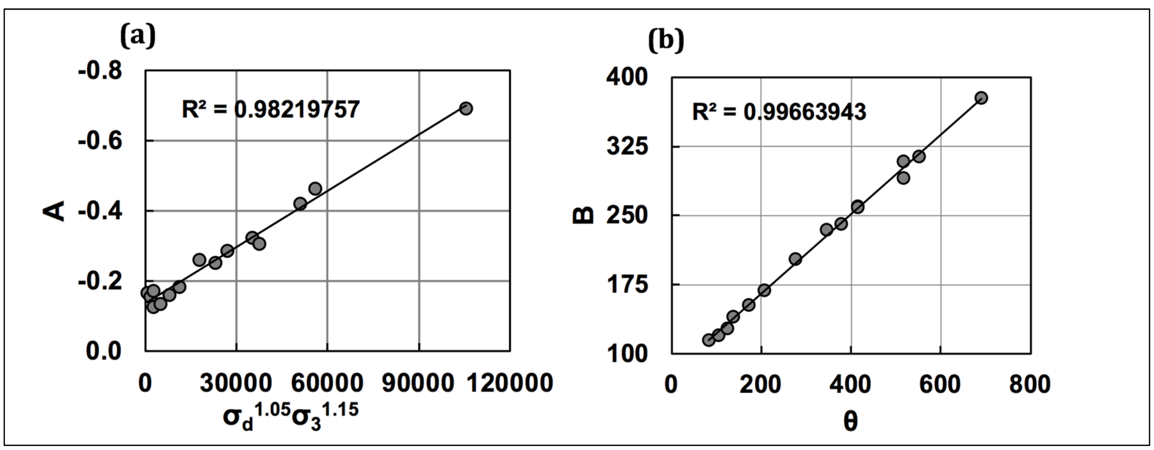

Figure 6-4 Relationships between (a) A and deviatoric stress and confining stress (b) B and bulk stress

Pezo (1993) and Garg and Thompson (1997) proposed a stress parameter associated with the resilient modulus based on deviatoric and confining stress. The current research aimed to find a relationship between "A" values and stress, and "A" values and $\sigma_d^{N_2} \times \sigma_3^{N_3}$ was calibrated to reach the best coefficient of determination. Figure 6-4(b) presents the relationships between "A" value and obtained $\sigma_d^{N_2} \times \sigma_3^{N_3}$, as:

$$A = -5.3 \times 10^{-6} \times \sigma_d^{1.05} \times \sigma_3^{1.15} - 0.14 \quad (6.4)$$

After identifying these relationships, they were substituted for A and B in equation (6.1) to obtain equation (6.5).

$$M_r(MPa) = \left(-5.3 \times 10^{-6} \times \sigma_d^{1.05} \times \sigma_3^{1.15} - 0.14\right) \times \%RG + 0.43 \times \theta + 79.06 \quad (6.5)$$

In which σ_d, σ_3, and θ are in KPa and %RG is the percentage of recycled glass in the fine fraction of MG20. The predicted M_r based on the proposed model, are compared with the laboratory measured M_r in Figure 6-5. A good agreement was found between measured and predicted values with the use of the proposed model.

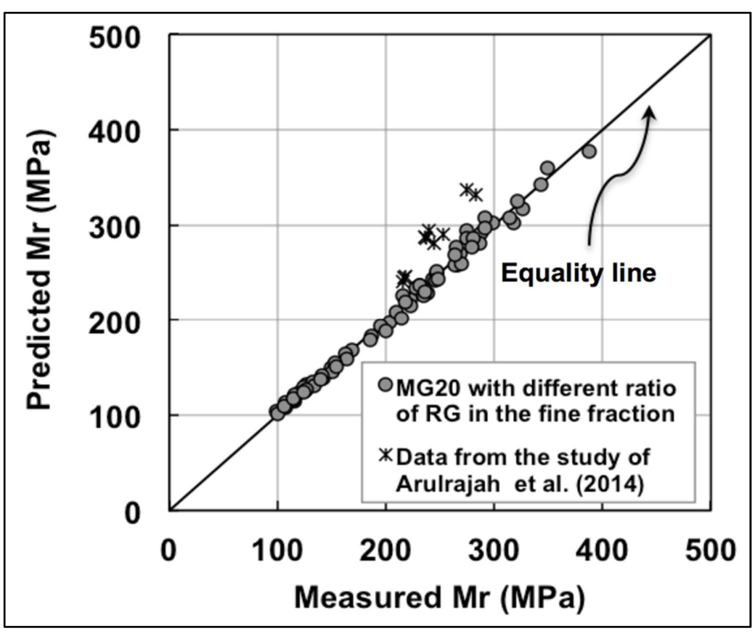

Figure 6-5 Predicted versus measured graph for the proposed model

To verify the proposed model predictive capacity, the data from the study conducted by Arulrajah et al. (2014) on the blends of RG and waste rock (WR) were considered, as presented in Figure 6-5. As it can be observed, the variation between predicted and measured values of M_r are less than 20% for materials studied by Arulrajah et al. (2014). The difference mentioned above can be explained by the variation of grain-size distribution, aggregate source, water content and test procedure between the current study and the study conducted by Arulrajah et al. (2014). The works of Bilodeau (Bilodeau, 2009) and Bilodeau et al. (Bilodeau et al., 2010) illustrated that for an identical size gradation, a variation of M_r of up to a factor of three may be found between the different source of aggregates. This fact can justify the observed differences regarding the different aggregate source of the current study and the study of Arulrajah et al. (2014), the limestone aggregate versus WR that is originated from basalt rock. Furthermore, Bilodeau (Bilodeau, 2009) showed that the grain-size distribution within a given grading envelope can affect the values of M_r for a given aggregate in a range of about 30%. Considering the differences as mentioned earlier, the 20% difference between the predicted and measured values for the Arulrajah et al. (2014) study can be considered acceptable, and the proposed model can reasonably predict the effect of recycled glass content on resilient modulus.

6.4.2 Permanent Strain Behavior

Figure 6-6 (a) illustrates the effect of stress ratio on the permanent strain of the blends of MG20 with RG. In this study, the different values of confining pressure (σ_3), from 21 through 138 KPa, were considered for each blend. For each step of confining pressure, the deviatoric stress (q) increased to three levels leading to an increase in the stress ratio (deviator stress to confining pressure ratio). It is obvious that increasing deviatoric stress directly increased the permanent strain when the confining pressure was constant. This finding is in agreement with the findings of Gräbe and Clayton (Gräbe & Clayton, 2009) and Li et al. (Li et al., 2017).

Figure 6-6(b) also presents the accumulation of permanent strain for the blends of MG20 with RG during the 15 test steps during which 100 loading cycles were applied. The accumulated permanent strain of all blends followed an upward trend with the number of load cycles during the tests, similar to what was shown by Craciun and Lo and Lekarp et al. (Craciun, 2009; Lekarp et al., 2000b) for other materials. Hence, the results obtained by previous researchers on materials that did not contain recycled glass, are also valid for the blends studied in this research. Based on the results presented in this study, an upward trend was found for recoverable deformation according to the increase of RG content. However, the permanent deformation did not follow an upward or downward trend. To evaluate the effects of using RG on the permanent deformation of the blends, and also to refine the accurate observations about permanent deformation in this study, conducting permanent deformation tests as part of the resilient modulus tests is advised.

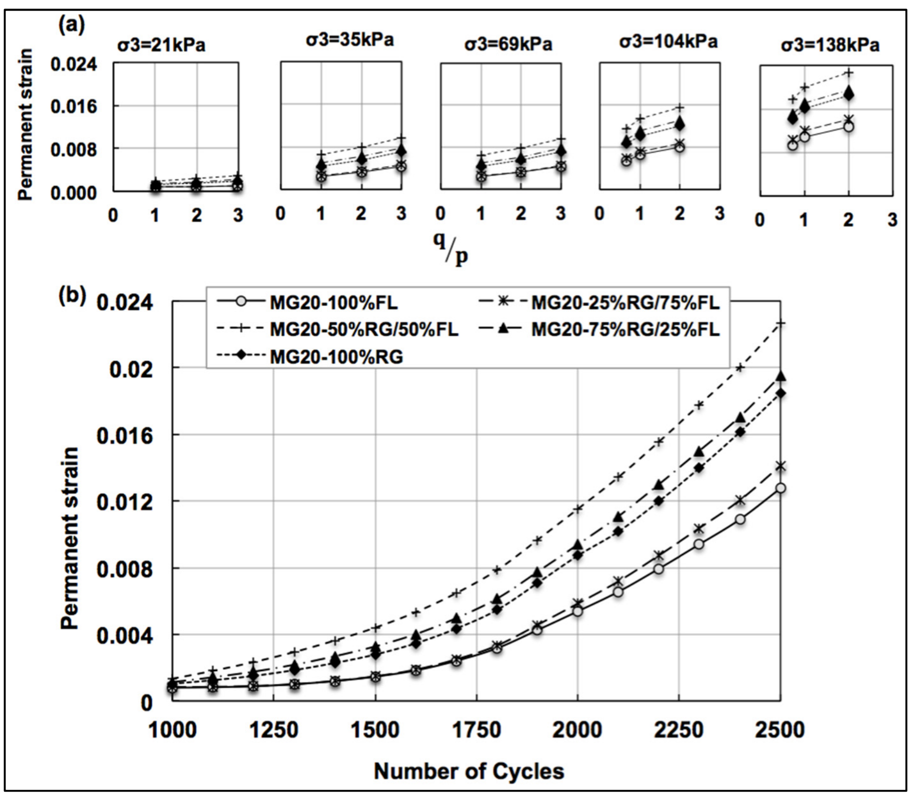

Figure 6-6 Permanent strain during resilient modulus test for MG20 with recycled glass

6.4.3 Shear Strength Behavior

Quick shear tests were performed at the end of the resilient modulus tests to evaluate the shear strength of specimens. The confining pressure was kept constant at 34 KPa during the shear test.

The deviatoric stress increased so that an axial strain rate of 1 percent per minute was maintained, under a strain-controlled loading procedure. Figure 6-7 shows the deviatoric stress versus axial strain for different MG20-FL/RG specimens. From Figure 6-7, it is obvious that MG20-100%FL hit the maximum shear strength. The shear strength of blends decreased when the RG content was increased. With increasing the amount of RG, the shape of shear stress-strain charts becomes similar to dense sand. Shear strength is described as the ultimate stress level that the material can undergo (Holtz & Kovacs, 1981). For granular materials, the load capacity is supported primarily by interparticle friction mechanism. The factors influencing the interparticle friction include particle surface texture, particle shape, void ratio, the degree of compaction, and particle gradation (CWC, 1998).

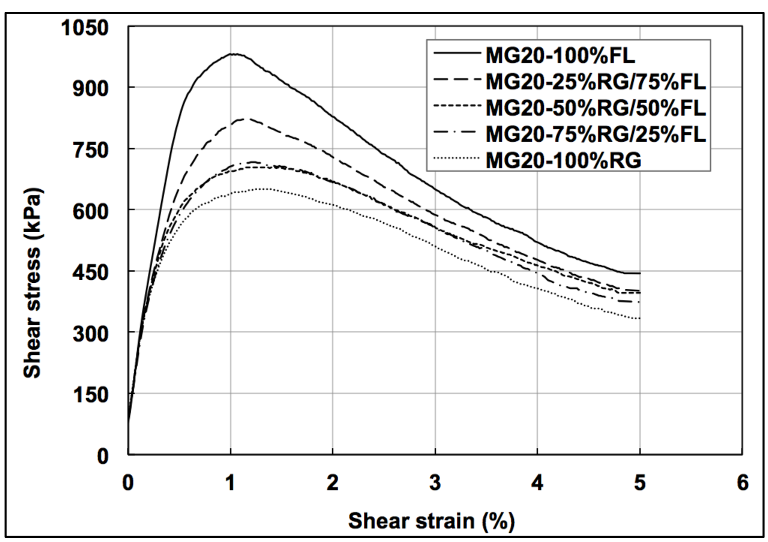

Figure 6-7 Shear stress test on the MG20 mix with recycled glass aggregate at confining pressure of 34 KPa in repeated triaxial test

For the tested blends, the particle surface texture and shape are believed to affect the shear strength of blends. The results of flow tests showed the higher angularity or rougher surfaces of limestone particles or the combination thereof, than recycled glass particles (Table 6-1). Hence, it is supposed that the shear strength of the blends of MG20 with RG increases when the content of RG decreases.

Similar studies on the quick shear tests at the end of resilient modulus tests were not found for RG blends based on the literature review. However, the researchers so far studied the shear strength properties of recycled glass aggregate and blends with some natural aggregates with direct shear test and triaxial shear test (Ali & Arulrajah, 2012; CWC, 1998; Disfani et al., 2011a; Disfani et al., 2012; Grubb et al., 2006a; Ooi et al., 2008; Wartman et al., 2004a; Wartman et al., 2004b). It is reported that recycled glass aggregate shows shear strength properties similar to those of well-graded sand, well-graded gravel or sand and gravel mixtures in dense conditions.

From Figure 6-7, there is a gradual decrease of shear strength for blends with increasing RG up to 25%RG. There is approximately a 16% decrease in shear strength values from MG20 to MG20 with 25%RG while the decrease goes to 34% by increasing RG ratio to 100% for the fine fraction in the mix. This study conducted the quick shear test under one value of confining pressure. It means further study should be done to determine the complete failure envelope and refine the noticed trends.

6.4.4 Conclusion

In this research, an extensive study was conducted on the laboratory characterization of blends of crushed limestone and recycled glass (RG) aggregates with granular base layer gradation characteristics. The size range of limestone aggregate was varied from 0-20 mm, based on MG20 gradation curve, and RG was in the range of 0-5 mm. To prepare the specimens, limestone aggregate was replaced by RG for five different contents, using a volumetric method as discussed in this article. The experimental study evaluated the resilient modulus behavior of RG blends. The findings led to present a prediction model for resilient modulus, M_r as well as an optimum ratio for adding RG to the blends of MG20, and some advice for using RG aggregate as materials for base layers of pavement. The major points can be summarized as in the following:

In this study, the change of three mechanical parameters, M_r, permanent strain, and shear strain, were evaluated while the RG aggregate was integrated into the fraction of MG20. The results showed increasing RG from 0 through 100%, in the blends of MG20, had less effect on the M_r values comparing to other parameters.

Based on the results of this study, the optimum content of RG aggregate in the fine fraction of MG20 was limited to 25%. As discussed before, this amount had minimum effect on M_r comparing to other ratios of RG. It is interesting to mention that 25%RG in the fine fraction of MG20 is corresponding to 11.4% of total volume of MG20 since the fine fraction of MG20 is defined between 0-5 mm while the whole range of MG20 is 0-20 mm.

Although the value of M_r decreased with increasing the RG amount, recycled glass can be used in the different ratio, even more than 25% in the base or subbase layer, depending on the roadwork applications and the stress distribution through the structural layers. Based on LC-22-400 (MTMDET, 2007), the value of M_r can be as low as 100 MPa for the structural layer used in lower in the pavement structure.

The permanent deformation of all blends followed an upward trend when the ratio of deviatoric stress to confining pressure and number of load repetitions were increased.

The shear strength of all blends decreased with RG contents. With increasing amount of RG, the shape of stress-strain charts became more similar to the one of dense sand. Furthermore, based on shear test results, the shear strength of blends of MG20 decreased with the addition of RG.

The suggested model for predicting M_r values based on %RG and stress levels agree with the experimental measured M_r values. It means this model can be used for engineering proposes to predict the M_r values for the various ratio of RG in MG20 under desired stress level.

This is a limited analysis including only limestone aggregate as the reference material and recycled glass. Study on other materials, with other characteristics, may give different results. The reader should consider carefully if the materials presented here, match the ones he or she is interested in, before applying the equations given in the paper.

Furthermore, the optimum percentage of RG, 25%, may increase in future studies in which specimens containing RG between 25% and 50% would be tested.

DISCUSSION AND CONCLUSION

Recycling glass remains a challenge in Quebec. Regarding sustainable development policy, the government of Quebec has aimed to increase the rate of recycling of such material. Achieving this objective demands to find an innovative approach of reusing the glass. Reusing recycled material in the geotechnical engineering and roadwork has proved great attraction. However, it is necessary to note that pavement materials, including those containing recycled material, must have properties that provide the required service life of the pavement.

The main objective of this research is to increase the high-added value usage of recycled glass (RG) through studying the advantages and limits of using RG in unbound granular layers of pavement structures. The focus of research is to investigate the hydraulic and mechanical aspects of using RG in base course, which has major roles in the performance of pavement base course structure. To achieve these objectives, this dissertation aims to answer two questions. First, how RG particles can improve the hydraulic behaviour of base course aggregate? Specifically, what is the effect of using RG on movement of water in the pavement structure? Secondly, what is the mechanical performance of the blends of natural aggregate with RG? Specifically, how RG influences on the load distribution of unbound pavement layers?

To answer the aforementioned questions, an experimental plan was prepared. The work has been done to identify the impact of RG on the hydraulic and mechanical behaviour of blends. The program was separated into three phases, and each phase was presented in the format of a journal paper in separate chapters, through chapters four, five, and six. An implication of the obtained results, as well as the most important closing remarks relevant to each chapter, and their contribution to the performance of pavement structure are discussed below.

One of the major roles of base course aggregate is providing adequate drainage of moisture that enters in pavement structure. The drainage performance of unbound layers can be investigated through studying the hydraulic properties of base course aggregate. These properties are evaluated through some laboratory tests including shape property, water absorption, specific gravity, compaction, hydraulic conductivity, and water retention. The research findings indicate that RG blends can improve the hydraulic performance of base/subbase course. As, increasing the RG ratio in blends improves three major investigated hydraulic properties including hydraulic conductivity, drainability, and water absorption. In terms of drainability, RG tends to enhance the drainage capacity of base course materials, as RG blends show lower air entry value and higher pore-size distribution than reference base course blend MG20/100%FL. Furthermore, RG aggregate shows negligible water absorption, which contributes to a better performance of aggregates against the development of absorbed water pressure during the freeze-thaw cycle in cold regions like Quebec. From hydraulic conductivity point, the blends with higher RG ratio show higher hydraulic conductivity than MG20/100%FL. It comes from smoother surface texture and lower specific surface area of fines of RG aggregate than crushed limestone, which are observed during experimental studies. These beneficial hydraulic properties can lead to potential of replacing up to 100% of the fine fraction (0-5 mm) of base course aggregate from hydraulic viewpoint. However, the mechanical aspects should be considered as well to suggest the optimum ratio of replacing. Based on assessing the existing experimental models to predict the hydraulic conductivity of aggregate, the methods of Hazen-Taylor, Kozeny-Carman, and Chapuis provide fair predictions for RG aggregate.

Another major role of base course is providing sufficient support and appropriate structural capacity of pavement system, which are in direct relation with the mechanical properties of base course aggregate. In this study a detailed laboratory investigation was undertaken to examine the effect of RG on the mechanical properties of RG blends through compaction, Los Angeles (LA), Micro-Deval, and California bearing ratio (CBR) tests. Durability, bearing capacity, and compaction properties as the major mechanical parameters are evaluated. The results prove that RG blends satisfy the mechanical expectations of road authorities as base/subbase course. In term of durability, RG blends improves the base course behaviour in presence of water based on Micro-Deval test results, which is similar to the field situation during compaction. However, in dry condition, RG aggregate shows lower durability than crushed limestone based on LA tests while remains above the minimum requirement of durability for base/subbase course. Comparing the results of LA and Micro-Deval reveals the importance of conducting both tests to evaluate the durability of materials in both dry and wet conditions. While MG20-RG blends have better durability in wet condition, its lower durability cannot be observed without conducting LA test. Based on CBR test results, MG20-RG blends have lower bearing capacity than MG20 with limestone. However, all MG20-RG blends meet the minimum CBR required for base/subbase course. It means that MG20-RG blends can be used as a base course aggregate from mechanical aspect. Also, a simple model was suggested for predicting the resilient modulus (M_r) of various MG20-RG blends, under the range of mean stress levels, based on the results of CBR tests. This model is beneficial for engineering design applications since CBR test is a relatively easy and inexpensive test to characterize the bearing capacity of aggregate in comparison with M_r test.

Furthermore, base course protects subgrade from significant deformation due to traffic loading. In other words, the unbound layers play an important role in the distribution of the traffic loads through underlying layers, and consequently, are essential to ensure the adequate overall performance of the pavement system. Therefore, understanding the response of base course aggregates with RG under traffic loading is critical. The deformation responses of granular materials under repeated loads are described by a resilient and a permanent strain response, which are evaluated through repeated triaxial test in this study. The finding of this study shows that M_r of MG20-RG blends decreases by increasing the ratio of RG. However, the reduction of M_r is not significant up to 25%RG in blends. Despite the fact that RG spreads load less than crushed limestone, it can be used in the different ratio in base/subbase layer depending on the roadwork application and the stress distribution through the structural layer. It means that the higher ratio of RG can be used in base/subbase course of the roads with lower traffic load. The recoverable deformation of MG20-RG blends follows an upward trend by increasing RG ratio. However, the permanent deformation did not follow an upward or downward trend. Conducting a permanent deformation test is required and recommended to evaluate the effects of using RG on the permanent deformation and also to refine the accurate observations about permanent deformation. Based on the quick shear test at the end of M_r test, a gradual decrease of shear strength for MG20-RG blends is observed by increasing RG up to 25% and this trend continues by increasing the RG ratio. Since M_r is one of the required inputs for flexible pavement design, a model is proposed in this study for predicting M_r values of MG20-RG blends based on the percentage of RG in the blends. This model can be integrated during the design process to avoid of conducting the M_r test, which is an expensive and complicated test.

This dissertation makes a good contribution to solve the RG challenge in the province of Quebec and to better understanding the impact of using RG on the performance of pavement structure. Overall, the following conclusion remarks can be drawn from this research:

The properties of RG aggregate shows that this recycled material could be safely used in pavement base/subbases courses regarding hydraulic aspects. RG blends can provide adequate drainage, which is beneficial to the pavement performance during the freeze-thaw cycles. In other words, the MG20-RG blends can contribute a satisfying global hydraulic performance of pavements since it has good drainage capacity to dissipate any excess water and limit the moisture damage. This matter improves the life cycle of pavement structure. Using RG blends helps to keep the pavement system from becoming saturated or even being subjected to high moisture content over time, which is a main objective in pavement design.

RG blends has potential to be used as base course aggregate, from mechanical aspects. Although RG aggregate has some weaker mechanical properities than limestone in some cases like CBR and LA loss, it meets all base course requirements. RG can be used in different ratio in the base or subbase layer, depending on the roadwork applications and the stress distribution through the structural layers. From resilient modulus, deformation and shear test aspects, RG blends can be used as base/subbase course aggregate however the ratio of RG in blends should be determined based on the application and traffic load level of the road.

In order to meet engineering requirements in road design, it is recommended the ratio of RG is limited up to 25% of replacing the fine fraction (0-5mm) of MG20 in base/subbase of roads. This ratio is recommended via considering all hydraulic and mechanical aspects as well as M_r. The critical parameters in determining this limit are M_r and deformation, which are affected by higher ratio of RG negatively. However, the higher ratio of RG can be used if the road design criteria are satisfied considering the calculated M_r and deformation of RG blend. In other words, the ratio of RG can go further than 25% in base/subbase of roads with lower traffic load or importance level of application.

The proposed model for M_r values of RG blends can predict the M_r appropriately. This model can be used in design process of base course to predict the $\mathrm{M_r}$ values for the various ratio of RG in MG20 under desired stress level regarding the limitation. However, this is a limited analysis including only crushed limestone as the reference material and RG. Study on other materials, with other characteristics, may give different results. The reader should consider carefully if the materials presented here, match the ones he or she is interested in, before applying the equations.

It is suggested to use the volumetric replacement method for combining RG with limestone aggregate in future research studies to ensure that the specific volume of reference material is replaced with the same volume of RG. Furthermore, as part of this replacement procedure, the aggregates are replaced by the same sizes of RG. Therefore, the gradation of the granular reference material remains the same for all the specimens tested.

This research improves the knowledge on both mechanical and hydraulic behaviours of RG blends as well as the properties of RG as an aggregate in base/subbase corse, including the hydraulic conductivity and the soil-water characteristic curve (SWCC) of blends with RG, durability, bearing capacity, M_r, and deformation. These parameters are deterministic in engineering analysis and design of base/subbase course of road.

This research put a foundation for usage of recycle glass as base/subbase course aggregate, which increases the high-added value usage of RG. This matter can contribute to environmental problems of backfilling the recycle glass. However, more on-site investigations are needed to define a practical procedure of using RG in field.

Although the focus of this study is on using RG as base/subbase course aggregate, the results of investigated mechanical and hydraulic properties can open the door to usage of RG aggregate in other fields. In other words, the usage of RG aggregates can go further than base/subbase courses of pavement as it has the potential of many high added-value usages such as drainage layer, compacted fill and trench backfill. However, more investigations should be conducted on specific situations and requirements of such usages.

All conclusion, results and recommendations are limited to the boundaries of this research, from materials to methods. Further studies and verification for future applications of the results of this study are essential to consider the unforeseen situations of this study.

RECOMMENDATIONS FOR FUTURE STUDIES

Based on the results of this study and the literature review the following recommendations have been made for future research work in this field.

- Settlement prediction of RG-limestone blends in base/subbase course of pavement using a finite element analysis based on the experimental data.

- Field monitoring (settlement and pore water pressure) of base/subbase course of pavement built using RG-limestone mixtures.

- Behaviour Investigation of RG-limestone aggregate blends under cyclic loading in a laboratory model to investigate the permanent deformation of blends.

- Recycling and reusing potential of the base/subbase course of pavement structure built using RG-limestone blends.

REFERENCES

AASHTO. (2003). Standard method of test for determining the resilient modulus of soils and aggregate materials. Standard method t 307. In (Vol. 99). American Association of State Highway and Transportation Officials, Washington D.C., USA.

Alexandria, V. (2013). *The aggregates handbook*: NationalStoneAssociation.

Ali, M., & Arulrajah, A. (2012). *Potential use of recycled crushed concrete-recycled crushed glass blends in pavement subbase applications.* Paper presented at the GeoCongress 2012.

Ali, M. M. Y., Arulrajah, A., Disfani, M. M., & Piratheepan, J. (2011). *Suitability of using recycled glass-crushed rock blends for pavement subbase applications.* Paper presented at the Geo-Frontiers Congress 2011.

Alonso, E. (1998). *Suction and moisture regimes in roadway bases and subgrades.* Paper presented at the INTERNATIONAL SYMPOSIUM ON SUBDRAINAGE IN ROADWAY PAVEMENTS AND SUBGRADES, HELD GRANADA, SPAIN, 11-13 NOVEMBER 1998.

Amlashi, S. M. H., Vaillancourt, M., & Carter, A. (2015). Current State of the Art Practice of Use of Glass in Pavement Structures. In TAC 2015: Getting You There Safely-2015 Conference and Exhibition of the Transportation Association of Canada.

Amlashi, S. M. H., Vaillancourt, M., Carter, A., & Bilodeau, J.-P. (2018). Resilient modulus of pavement unbound granular materials containing recycled glass aggregate. *Materials and Structures, 51*(4), 89.

Apul, D. S., Gardner, K., Eighmy, T., Benoit, J., & Brannaka, L. (2002). A review of water movement in the highway environment: Implications for recycled materials use. *Recycled Materials Resource Center, University of New Hampshire, Durham, New Hampshire*, 112-112.

ARA, I. (2004). Guide for mechanistic-empirical design of new and rehabilitated pavement structures. In: Part.

Arulrajah, A., Ali, M. M. Y., Disfani, M. M., & Horpibulsuk, S. (2014). Recycled-glass blends in pavement base/subbase applications: Laboratory and field evaluation. *Journal of Materials in Civil Engineering, 26*(7), 04014025 (04014012 pp.). doi:10.1061/(ASCE)MT.1943-5533.0000966

Arulrajah, A., Ali, M. M. Y., Disfani, M. M., Piratheepan, J., & Bo, M. W. (2013). Geotechnical performance of recycled glass-waste rock blends in footpath bases.

Journal of Materials in Civil Engineering, 25(5), 653-661. doi:10.1061/(ASCE)MT.1943-5533.0000617

Arulrajah, A., Piratheepan, J., Disfani, M. M., & Bo, M. W. (2012). Geotechnical and geoenvironmental properties of recycled construction and demolition materials in pavement subbase applications. *Journal of Materials in Civil Engineering*(August), 120829040349008-120829040349008. doi:10.1061/(ASCE)MT.1943-5533.0000652

Arulrajah, A., Piratheepan, J., Disfani, M. M., & Bo, M. W. (2013). Geotechnical and geoenvironmental properties of recycled construction and demolition materials in pavement subbase applications. *Journal of Materials in Civil Engineering, 25*(8), 1077-1088. doi:10.1061/(ASCE)MT.1943-5533.0000652

ASTM. (2006). Standard test method for permeability of granular soils (constant head). Astm international. Astm standard d2434 - 06. In (Vol. 10, pp. D0422). West Conshohocken, PA 19428-2959. United States.

ASTM. (2008). Standard test methods for determination of the soil water characteristic curve for desorption using hanging column, pressure extractor, chilled mirror hygrometer, or centrifuge. Astm standard d6836 - 08. In. West Conshohocken, PA 19428-2959, United States.

ASTM. (2011). D2487 standard practice for classification of soils for engineering purposes (unified soil classification system). *ASTM International, West Conshohocken, PA www. ASTM. org*.

ASTM. (2012a). D1557, 2012. Standard test methods for laboratory compaction characteristics of soil using modified effort (56,000 ft-lbf/ft3 (2,700 kn-m/m3)). Astm international, west conshohocken, pa. In: ASTM International, West Conshohocken, PA.

ASTM. (2012b). Standard test method for measuring the filtration compatibility of soil-geotextile systems. Astm standard d5101 - 12. In. West Conshohocken, PA 19428-2959, United States.

ASTM. (2014a). Standard test method for resistance to degradation of small-size coarse aggregate by abrasion and impact in the los angeles machine. Astm standard c131-14. In. West Conshohocken, PA 19428-2959, United States.

ASTM. (2014b). Standard test methods for specific gravity of soil solids by water pycnometer method. Astm standard d854-14. In. West Conshohocken, PA 19428-2959, United States.

ASTM. (2015a). Standard test method for density , relative density (specific gravity), and absorption of fine aggregate. Astm standard c128 - 15. In (Vol. i, pp. 1-6). West Conshohocken, PA 19428-2959, United States.

ASTM. (2015b). Standard test method for resistance of fine aggregate to degradation by abrasion in the micro-deval apparatus. Astm standard d7428-15. In. West Conshohocken, PA 19428-2959, United States.

ASTM. (2016a). Standard test method for cbr (california bearing ratio) of laboratory-compacted soils. Astm standard d1883-16. In (Vol. 4). West Conshohocken, PA 19428-2959, United States.

ASTM. (2016b). Standard test methods for maximum index density and unit weight of soils using a vibratory table. Astm standard d4253 - 16. In. West Conshohocken, PA 19428-2959, United States.

ASTM. (2016c). Standard test methods for minimum index density and unit weight of soils and calculation of relative density. Astm standard d4254 - 16. In. West Conshohocken, PA 19428-2959, United States. .

ASTM. (2017). Standard practice for classification of soils for engineering purposes (unified soil classification system). Astm standard d2487-17. In. West Conshohocken, PA 19428-2959, United States. .

Aubertin, M., Mbonimpa, M., Bussière, B., & Chapuis, R. (2003). A model to predict the water retention curve from basic geotechnical properties. *Canadian Geotechnical Journal, 40*(6), 1104-1122.

Ayres, M. (1997). *Development of a rational probabilistic approach for flexible pavement analysis.* University of Maryland, College Park, Md.,

Bessa, I. S., Castelo Branco, V. T. F., & Soares, J. B. (2014). Evaluation of polishing and degradation resistance of natural aggregates and steel slag using the aggregate image measurement system. *Road Materials and Pavement Design, 15*(2), 385-405.

Bilodeau, J. (2009). Optimisation de la granulométrie des matériaux granulaires de fondation des chaussées [dissertation phd]. *Québec: Université Laval.*

Bilodeau, J.-P., & Doré, G. (2012). Water sensitivity of resilient modulus of compacted unbound granular materials used as pavement base. *International Journal of Pavement Engineering, 13*(5), 459-471.

Bilodeau, J.-P., Dore, G., & Pierre, P. (2010). Optimisation de la granulométrie des matériaux granulaires de fondation des chaussées. *Canadian Journal of Civil Engineering, 37*(10), 1350-1362.

Bilodeau, J.-P., Plamondon, C. O., & Doré, G. (2016). Estimation of resilient modulus of unbound granular materials used as pavement base: Combined effect of grain-size distribution and aggregate source frictional properties. *Materials and Structures, 49*(10), 4363-4373.

BNQ. (2002). Granulats – matériaux recyclés fabriqués à partir de résidus de béton, d'enrobés bitumineux et de briques – classification et caractéristiques. Nq2560-600. In. Bureau de normalisation du Québec (BNQ).

BNQ. (2014). Granulats - travaux de génie civil. In. Bureau de normalisation du Québec. .

Brooks, R., & Corey, T. (1964). Hydrau uc properties of porous media. *Hydrology Papers, Colorado State University, 24*.

Caillou, A. (2017). Le verre, la bête noire du recyclage au québec. Retrieved from https://www.ledevoir.com/societe/environnement/507237/le-verre-la-bete-noire-du-recyclage-au-quebec

CAN/BNQ. (1982). Granulats-essai au bleu de méthylène. Canadian standards association (ottawa, ont.) and bureau de normalisation du québec (québec, que.). Can/bnq 2560–255.

Cerni, G., Cardone, F., Virgili, A., & Camilli, S. (2012). Characterisation of permanent deformation behaviour of unbound granular materials under repeated triaxial loading. *Construction and Building Materials, 28*(1), 79-87.

Chapuis, R. P. (2012). Predicting the saturated hydraulic conductivity of soils: A review. *Bulletin of engineering geology and the environment, 71*(3), 401-434.

Chapuis, R. P., & Aubertin, M. (2003). On the use of the kozeny carman equation to predict the hydraulic conductivity of soils. *Canadian Geotechnical Journal, 40*(3), 616-628.

Corinaldesi, V., Gnappi, G., Moriconi, G., & Montenero, A. (2005). Reuse of ground waste glass as aggregate for mortars. *Waste Management, 25*(2), 197-201.

Cossio, M. L. T., Giesen, L. F., Araya, G., Pérez-Cotapos, M. L. S., Vergara, R. L., Manca, M., . . . Héritier, F. (2012). *No title no title* (Vol. XXXIII).

Côté, J., & Konrad, J.-M. (2003). Assessment of the hydraulic characteristics of unsaturated base-course materials: A practical method for pavement engineers. *Canadian Geotechnical Journal, 40*(1), 121-136.

Craciun, O. (2009). *Matric suction response of unbound granular base materials subject to cyclic loading.* Australian Defence Force Academy,

Craciun, O., & Lo, S.-C. R. (2009). Matric suction measurement in stress path cyclic triaxial testing of unbound granular base materials.

CWC, C. W. C. (1998). *A tool kit for the use of post-consumer glass as a construction aggregate*. Retrieved from

Dawson, A. (1995). *The unbound aggregate pavement base.* Paper presented at the Center for Aggregates Research, 3rd Annual Symposium, Austin, Texas.

DeLong, C. M., Bragg, R., & Simmons, J. A. (2008). Evidence for spatial representation of object shape by echolocating bats (*eptesicus fuscus*). *Journal of the Acoustical Society of America, 123*(6), 4582-4598. doi:10.1121/1.2912450

Disfani, M. (2011). *Sustainable use of recycled glass-biosolids blends in road application.* PhD Thesis, Faculty of Engineering and Industrial Sciences, Swinburne University of Technology, Melbourne, Australia,

Disfani, M., Arulrajah, A., Ali, M., & Bo, M. (2011b). Fine recycled glass: A sustainable alternative to natural aggregates. *International Journal of Geotechnical Engineering, 5*(3), 255-266.

Disfani, M. M., Arulrajah, A., Bo, M. W., & Hankour, R. (2011a). Recycled crushed glass in road work applications. *Waste Management, 31*(11), 2341-2351. doi:10.1016/j.wasman.2011.07.003

Disfani, M. M., Arulrajah, A., Bo, M. W., & Sivakugan, N. (2012). Environmental risks of using recycled crushed glass in road applications. *Journal of Cleaner Production, 20*(1), 170-179. doi:10.1016/j.jclepro.2011.07.020

Doré, G., & Zubeck, H. K. (2009). *Cold regions pavement engineering*.

Dragonfly. (2004). Object research systems (ors) inc, dragonfly 3dversion 3.5, http://www.Theobjects.Com/dragonfly/index.Html.

Erdoğan, S. T. (2005). *Determination of aggregate shape properties using x-ray tomographic methods and the effect of shape on concrete rheology.*

Erlingsson, S. (2007). On forecasting the resilient modulus from the cbr value of granular bases. *Road Materials and Pavement Design, 8*(4), 783-797.

Erlingsson, S., & Magnusdottir, B. (2004). *Comparison between stiffness values from rltt and cbr-values for unbound granular materials.* Paper presented at the Proceedings of the Nordic Geotechnical Conference–NGM, Swedish Geotechnical Society, May.

FHWA, F. H. A. (1998). *User guidelines for waste and by-product materials in pavement construction*. Retrieved from

FHWA, F. H. A. (2006). *Geotechnical aspects of pavements* (FHWA NHI-05-037). Retrieved from

Finkle, I., Ksaibati, K., & Robinson, T. (2007). *Recycled glass utilization in highway construction*. Retrieved from

Fredlund, D. G., & Xing, A. (1994). Equations for the soil-water characteristic curve. *Canadian Geotechnical Journal, 31*(4), 521-532.

Gagné, L. (2010). Le verre: Fiches informatives. 8.

Gallage, C. P. K., & Uchimura, T. (2010). Effects of dry density and grain size distribution on soil-water characteristic curves of sandy soils. *Soils and foundations, 50*(1), 161-172.

Garg, N., & Thompson, M. (1997). Triaxial characterization of Minnesota Road Research project granular materials. Transportation Research Record: Journal of the Transportation Research Board, (1577), 27-36.

Ghabchi, R., Zaman, M., Kazmee, H., & Singh, D. (2014). Effect of shape parameters and gradation on laboratory measured permeability of aggregate bases. *International Journal of Geomechanics, 14*(3), pp 04014070 (04014071-04014011). doi:10.1061/(ASCE)GM.1943-5622.0000397

Ghabchi, R., Zaman, M., Khoury, N., Kazmee, H., & Solanki, P. (2013). Effect of gradation and source properties on stability and drainability of aggregate bases: A laboratory and field study. *International Journal of Pavement Engineering, 14*(3), 274-290.

Gonzalez, C. R. (2015). *Development and validation of a stress-based procedure for the design of military flexible pavements*: University of Illinois at Urbana-Champaign.

Gräbe, P. J., & Clayton, C. R. (2009). Effects of principal stress rotation on permanent deformation in rail track foundations. *Journal of Geotechnical and Geoenvironmental Engineering, 135*(4), 555-565.

Green, J. L., & Hall, J. W. (1975). *Nondestructive vibratory testing of airport pavements. Volume 1. Experimental test results and development of evaluation methodology and procedure*. Retrieved from

Grubb, D. G., Davis, A. F., Sands, S. C., Carnivale, M., Wartman, J., & Gallagher, P. M. (2006a). Field evaluation of crushed glass–dredged material blends. *Journal of geotechnical and geoenvironmental engineering, 132*(5), 577-590. doi:10.1061/(ASCE)1090-0241(2006)132:5(577) CE

Grubb, D. G., Gallagher, P. M., Wartman, J., Liu, Y., & Carnivale III, M. (2006b). Laboratory evaluation of crushed glass–dredged material blends. *Journal of geotechnical and geoenvironmental engineering, 132*(5), 562-576.

Halstead, W. J. (1993). Use of waste glass in highway construction. *Update, 1*, 992.

Hatanaka, M., Uchida, A., Taya, Y., Takehara, N., Hagisawa, T., Sakou, N., & Ogawa, S. (2001). Permeability characteristics of high-quality undisturbed gravelly soils measured in laboratory tests. *Soils and foundations, 41*(3), 45-55.

Head, K. (1994). Vol. 2: Permeability, shear strength and compressibility tests.

Henry, K. S. and Morin, S. H. 1997. « Frost susceptibility of crushed glass used as construction aggregate ». Journal of cold regions engineering, vol. 11, no 4, p. 326-333.

Heukelom, W., & Klomp, A. (1962). *Dynamic testing as a means of controlling pavements during and after construction.* Paper presented at the International Conference on the Structural Design of Asphalt PavementsUniversity of Michigan, Ann Arbor.

Heydinger, A., Xie, Q., Randolph, B., & Gupta, J. (1996). Analysis of resilient modulus of dense-and open-graded aggregates. *Transportation Research Record: Journal of the Transportation Research Board*(1547), 1-6.

Hicks, R. G., & Monismith, C. L. (1971). Factors influencing the resilient response of granular materials. *Highway Research Record*(345).

Hoff, I. (1999). *Material properties of unbound aggregates for pavement structures*: Department of Road and Railroad Engineering, the Norwegian University of Science and Technology.

Holtz, R. D., & Kovacs, W. D. (1981). *An introduction to geotechnical engineering*.

Huang, Y., Bird, R. N., & Heidrich, O. (2007). A review of the use of recycled solid waste materials in asphalt pavements. *Resources, Conservation and Recycling, 52*(1), 58-73.

Khoury, N., Zaman, M., & Brooks, R. (2010). Stiffness and drainage characteristics of unbound aggregate bases. *International Journal of Geotechnical Engineering, 4*(4), 461-469.

Kolisoja, P., Saarenketo, T., Peltoniemi, H., & Vuorimies, N. (2002a). Laboratory testing of suction and deformation properties of base course aggregates. *Transportation Research Record: Journal of the Transportation Research Board*(1787), 83-89.

Lachance-Tremblay, E., Perraton, D., Vaillancourt, M., & Di Benedetto, H. (2017). Degradation of asphalt mixtures with glass aggregates subjected to freeze-thaw cycles. *Cold Regions Science and Technology, 141*, 8-15.

Lachance-Tremblay, É., Vaillancourt, M., & Perraton, D. (2016). Evaluation of the impact of recycled glass on asphalt mixture performances. *Road Materials and Pavement Design, 17*(3), 600-618.

Lambe, T. W., & Whitman, R. V. (1969). *Soil mechanics*.

Landris, T., & Lee, J. (2007). *Recycled glass and dredged materials*, ERDC TN-DOER-T8 March 2007.

Lane, B., Rogers, C., & Senior, S. (2000). *The micro-deval test for aggregates in asphalt pavement.* Paper presented at the th Annual Symposium of the International Center for Aggregate Research. Denver, Colorado.

Lekarp, F., Isacsson, U., & Dawson, A. (2000a). State of the art. I: Resilient response of unbound aggregates. *Journal of transportation engineering, 126*(1), 66-75.

Lekarp, F., Isacsson, U., & Dawson, A. (2000b). State of the art. Ii: Permanent strain response of unbound aggregates. *Journal of transportation engineering, 126*(1), 76-83.

Leong, E. C., & Rahardjo, H. (1997). Review of soil-water characteristic curve equations. *ASCE Journal of geotechnical and geoenvironmental engineering, 123*(12), 1106-1117.

Li, W., Wilson, D. J., Larkin, T. J., & Black, P. M. (2017). Permanent strain behavior of marginal granular material. *Transportation Research Record: Journal of the Transportation Research Board*(2655), 54-63.

Lister, N., & Powell, W. (1987). *Design practice for bituminous pavements in the united kingdom.* Paper presented at the international conference on the structural design, *Published at the Transportation Research Board (TRB).*

Lupien, C. (2006). *Projet pilote de valorisation du verre récupéré*. Retrieved from Rapport présenté à RECYC-QUÉBEC.

Mamlouk, M. S., & Zaniewski, J. P. (2011). *Materials for civil and construction engineers*: Prentice Hall Upper Saddle River, NJ.

Marshall, T. (1959). The diffusion of gases through porous media. *European Journal of Soil Science, 10*(1), 79-82.

Mbonimpa, M., Aubertin, M., Chapuis, R., & Bussière, B. (2002). Practical pedotransfer functions for estimating the saturated hydraulic conductivity. *Geotechnical & Geological Engineering, 20*(3), 235-259.

Meyer, C. (2001). Recycled glass–from waste material to valuable resource. *Proceedings of the International Syposium: Recycling and reuse of Glass Cullet, Dundee, Scotland*, 1-10.

Meyer, C., & Xi, Y. (1999). Use of recycled glass and fly ash for precast concrete. *Journal of Materials in Civil Engineering, 11*(2), 89-90.

Mishra, D., & Tutumluer, E. (2012). Aggregate physical properties affecting modulus and deformation characteristics of unsurfaced pavements. *Journal of Materials in Civil Engineering, 24*(9), 1144-1152.

Mohapatra, P. K., & Kumari, B. (2017). Behaviors of intermediate layer" base course" used on the construction of highway.

MTMDET. (2007). Détermination du module réversible des matériaux granulaires. Lc 22-400. In. Procédure de laboratoire, Ministère des Transports, de la Mobilité durable et de l'Électrification des transports, Québec.

MTMDET. (2015). Granulats – détermination du coefficient d'écoulement du granulat fin (lc 21-075). In. Procédure du laboratoire des chaussées, Ministère des Transports, de la Mobilité durable et de l'Électrification des transports, Québec.

Murray, E. (1995). *Prediction of permeability of granular materials.* Paper presented at the unbound aggregates in roads. proceedings of the fourth international symposium on unbound aggregates in roads (unbar4) held 17th-19th july 1995, university of nottingham.

Navfac, D. (1974). Design manual-soil mechanics, foundations, and earth structures. *US Government Printing Office, Washington, DC*.

NCHRP, N. C. H. R. P. (2003). *Final report—guide for mechanistic-empirical design of new and rehabilitated pavement design structures—part 2 design inputs—chapter 2: Material characterization*.

Ooi, P. S. K., Li, M. M. W., Sagario, M. L. Q., & Song, Y. (2008). Shear strength characteristics of recycled glass. *Transportation Research Record*(2059), 52-62. doi:10.3141/2059-06.

Pennsylvania, D. (2001). *Laboratory evaluation of select engineering-related properties of glass cullet. Pennsylvania department of transportation*. Retrieved from Arrisburg, Pennsylvania, USA: http://www.dot.state.pa.us/Internet/Bureaus/pdDesign.

Québec, G. (2011). Allier économie et environnement. Politique québécoise de gestion des matières résiduelles Plan d'action 2011-2015.

Rabaiotti, C., & Caprez, M. (2005). Compaction characteristics and bearing capacity of recycled materials for road construction. *ASCE Geotechnical Special Publication*(127).

Rahardjo, H., Vilayvong, K., & Leong, E. C. (2010). Water characteristic curves of recycled materials. *ASTM Geotechnical Testing Journal, 34*(1), 89-96.

Rahbar-Rastegar, R. (2017). *Cracking in asphalt pavements: Impact of component properties and aging on fatigue and thermal cracking.* University of New Hampshire,

Rahbar-Rastegar, R., Sias Daniel, J., & Reinke, G. (2017). Comparison of asphalt binder and mixture cracking parameters. *Road Materials and Pavement Design*, 1-23.

RECYC-QUÉBEC. (2012). De la gestion des matières résiduelles au québec-bilan 2012. Retrieved from https://www.recyc-quebec.gouv.qc.ca/sites/default/files/documents/bilan-gmr-2012.pdf.

Recyc-Québec. (2014). Le recyclage du verre au québec. Retrieved from http://bacsplus.ca/wp-content/uploads/2015/04/Fiche_info_verre-RQ-02-2015.pdf.

Recyc-Québec. (2015). Recovery, recycling and recovery of glass: The status that is no longer an option. Retrieved from https://www.recyc-quebec.gouv.qc.ca/haut-de-page/salle-de-presse/archives-presse/2015-recuperation-verre.

Reid, J., Evans, R., Holnsteiner, R., Wimmer, B., Gaggl, W., Berg, F., . . . Rathmeyer, H. (2001). Alternative materials alt_mat. *Final Report, Contract No. RO-97-SC, 2238*.

Richardson, D. N. (1997). Drainability characteristics of granular pavement base material. *Journal of transportation engineering, 123*(5), 385-392.

Rogers, C. (1998). Canadian experience with the micro-deval test for aggregates. *Geological Society, London, Engineering Geology Special Publications, 13*(1), 139-147.

Schwartz, C. W. (2002). Effect of stress-dependent base layer on the superposition of flexible pavement solutions. *International Journal of Geomechanics, 2*(3), 331-352.

Senadheera, S., Rana, A., & Nash, P. (2005). Characterization of the behavior of granular road material containing glass cullet. *7th International Conference on the Bearing Capacity of Roads Railways and Airfields BCRA05*.

Shah, K. (2007). *Effects of gradation and compaction energy on the hydraulic conductivity of an aggregate base commonly used in oklahoma.* University of Oklahoma,

Shahabi, A., Das, B., & Tarquin, A. (1984). An empirical relation for coefficient of permeability of sand.

Shayan, A., & Xu, A. (2004). Value-added utilisation of waste glass in concrete. *Cement and Concrete Research, 34*(1), 81-89.

Su, N., & Chen, J. (2002). Engineering properties of asphalt concrete made with recycled glass. *Resources, Conservation and Recycling, 35*(4), 259-274.

Taha, B., & Nounu, G. (2008). Properties of concrete contains mixed colour waste recycled glass as sand and cement replacement. *Construction and Building Materials, 22*(5), 713-720.

Tandon, V., & Picornell, M. (1997). Proposed evaluation of base materials for drainability. *Transportation Research Record: Journal of the Transportation Research Board*(1596), 62-69.

Tarrer, A. R., & Wagh, V. (1991). *The effect of the physical and chemical characteristics of the aggregate on bonding* (No. SHRP-A/UIR-91-507). Washington, DC, USA: Strategic Highway Research Program, National Research Council.

Tarmuzi, N., Jaya, R., Yaacob, H., Hassan, N., & Aziz, M. (2015). Aggregate angularity effect on porous asphalt engineering properties and performance. *Jurnal Teknologi, 73*(4), 99-104.

Taylor, D. (1948). *Fundamentals of soil mechanics*: Chapman And Hall, Limited.; New York.

Terzaghi, K. (1925). Principles of soil mechanics: Iii–determination of permeability of clay. *Engineering News-Record, 95*(21), 832-836.

Terzaghi, K., Peck, R. B., & Mesri, G. (1996). *Soil mechanics in engineering practice*: John Wiley & Sons.

Ullidtz, P. (1987). *Pavement analysis. Developments in civil engineering, 19*.

Van Genuchten, M. T. (1980). A closed-form equation for predicting the hydraulic conductivity of unsaturated soils 1. *Soil science society of America journal, 44*(5), 892-898.

van Niekerk, A. (2002). *Mechanical behavior and performance of granular bases and sub-bases in pavements*.

Wartman, J., Grubb, D. G., & Nasim, A. (2004a). Select engineering characteristics of crushed glass. *Journal of Materials in Civil Engineering, 16*(6), 526-539.

Wartman, J., Grubb, D. G., & Strenk, P. (2004b). *Engineering properties of crushed glass-soil blends* (0784407444). Retrieved from

Werkmeister, S. (2003). Permanent deformation behaviour of unbound granular materials in pavement constructions.

White, D. J., Vennapusa, P., & Jahren, C. T. (2004). *Determination of the optimum base characteristics for pavements*. Retrieved from

Wilk, G. D., Wallace, R. M., & Anthony, J. (2001). High-κ gate dielectrics: Current status and materials properties considerations. *Journal of applied physics, 89*(10), 5243-5275.

Witczak, M. W., Qi, X., & Mirza, M. W. (1995). Use of nonlinear subgrade modulus in aashto design procedure. *Journal of transportation engineering, 121*(3), 273-282.

Wolfe, A. J. (2011). *Behavior of composite pavement foundation materials subjected to cyclic loading*: Iowa State University.

WTIC. (1999). *Using recovered materials in highway construction*. Retrieved from Wisconsin Transportation Information Center:

Wyllie, M., & Gardner, G. (1958). The generalized kozeny-carman equation. *World oil, 146*(4), 121-128.

Yideti, T. F., Birgisson, B., & Jelagin, D. (2014). Influence of aggregate packing structure on california bearing ratio values of unbound granular materials. *Road Materials and Pavement Design, 15*(1), 102-113.

Yılmaz, A., & Yılmaz, A. (2016). Mechanical properties of basalt aggregates for use in unbound pavement layers.