Current State of the Art Practice of Use of Glass in Pavement Structures

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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.

1. 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.

2. 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 ((TIC), 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), 1996).

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 biosoilids when used alone can be removed by mixing them and also their strength properties can be increased (Disfani, 2011).

Table 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., 2006).

3. 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 2 presents the basic physical properties of recycled glass particles based on other 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., 2006). Properties and proportions of both the main soil and the recycled glass component affect the behavior of the mixture (Disfani, 2011). 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 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.

3.1. 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 4. As indicated in Table 4, typical modified compaction densities of recycled glass are between 18-19 kN/m^3 with optimum water contents of 5.7-7.5% based on FHWA ((FHWA), 1998). The maximum dry density ($\gamma_{d,\max}$) 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 $\gamma_{d,\max}$ 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. (2006) studied moisture-density relationships of crushed glass (CG)/dredged material (DM) blends. Increasing

CG content resulted in decreasing optimum moisture content and increasing $\gamma_{d,\max}$. From Table 4, it is evident that the values of $\gamma_{d,\max}$ usually stay within the limits of 100% CG and 0% CG (100% DM) (Grubb et al., 2006). 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., 2006). 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 ($G_{s\text{-glass}}$=2.48 versus $G_{s\text{-soil}}$=2.7) 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, $\gamma_{d,\max}$ of well graded soils is usually more than poorly-graded soils. At the higher soil proportions, the $\gamma_{d,\max}$ decreases due to the blends becoming more poorly graded (Wartman et al., 2004a).

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/m^3, and fine recycled glass had the lowest of 18.4 kN/m^3. 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).

3.2. 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 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 bends 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, about 25% based on the impact compactor and 50% based on the compactor ((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).

3.3. 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), 2014). 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 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. 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 (UU), 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 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. (Disfani et al., 2011b), while the values found by Wartman et al. (Wartman et al., 2004b) are a bit higher. The results of the mentioned studies proved that the friction angle of the recycled glass samples are comparable to those of dense and coarse natural aggregates ((CWC), 1998; (FHWA), 1998; Disfani et al., 2011b; Lambe et 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).

From Table 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. (2006) 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., 2006). Wartman et al. (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).

3.4.1. 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).

3.5. 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 1(a) and (b) respectively. Figure 1(a) reports hydraulic conductivity values between 0.000161 and 0.26 cm/s for 100% of pure recycled glass particles. From Figure 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 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; Grubb et al., 2006; 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 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 enhances 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 1(b). Grubb et al. (2006) 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 Figure 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., 2006).

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).

3.6. 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 is serious frost penetration below geotechnical structures like pavement (Henry and Morin, 1997). Henry and Moran (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).

4. SUMMARY OF LITERATURE REVIEW AND FUTURE WORK

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 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.

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Table 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	NA	(Wartman et al., 2004a)
Fills	20%-80%	Dredged material	NA	(Grubb et al., 2006)
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	NA	(Ali et Arulrajah, 2012)

Table 2. Basic physical properties of recycled glass particles

Reference	USCS Soil classification	Maximum particle size (mm)	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), 1997; 1998)	SW	19.2	9.8	1.5	2	70	28	2.49
(Su et Chen, 2002)	SP	4.75	4.4	1.2	1	99	0	2.54
(Wartman et al., 2004b)	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., 2006)	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 et Arulrajah, 2012)	SW	5	6.2	1.5	2.8	71.2	26	2.49
(Disfani et al., 2012)	FRG SW-SM	4.75	7.6	1.3	5.4	90	10	2.48
(Disfani et al., 2012)	MRG SW-SM	9.5	16.3	2.2	5.2	48	52	2.5

Table 3. Recommended glass gradation for use as a granular base material ((FHWA), 1998)

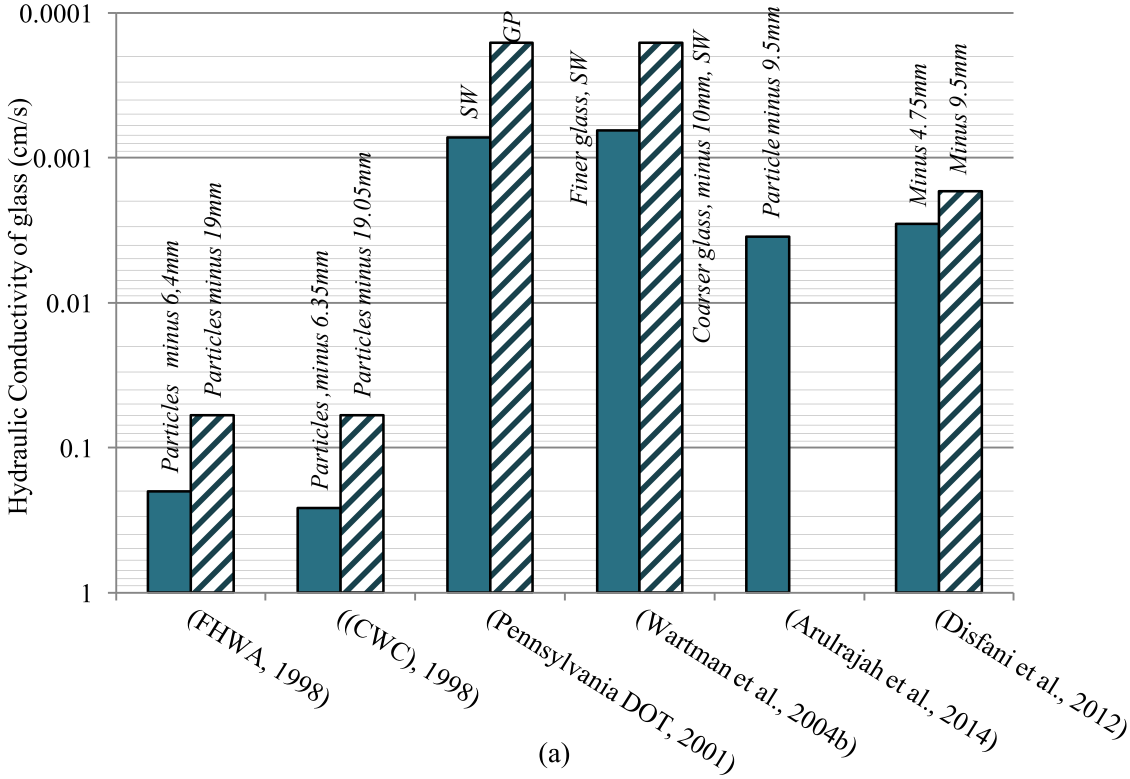
Size	% Finer
6.35 mm (1/4 in)	10 - 100
1.68 mm (No. 10)	0 - 50
0.42 mm (No. 40)	0-25
0.075 mm (No. 200)	0-5

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

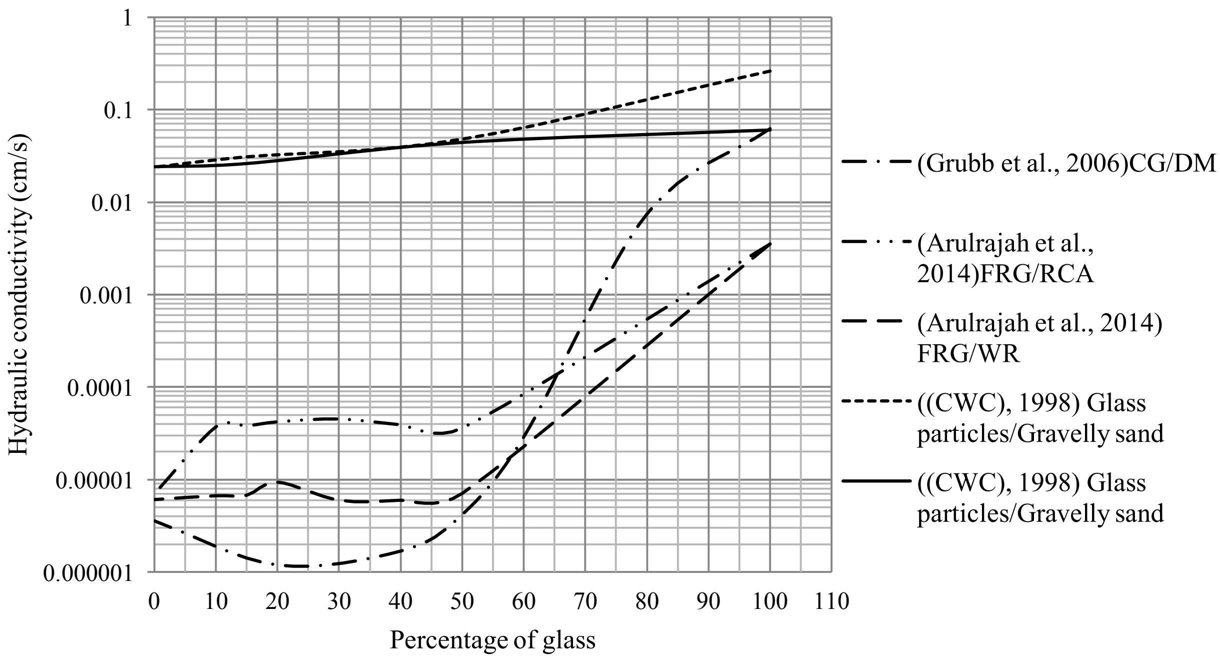
Reference	Recycled glass (%)	Blended material	Standard proctor max dry density (KN/m3)	Optimum Moisture (%)	Modified proctor max dry density (KN/m^3)	Optimum Moisture (%)	CBR (%)	LA loss(%)
((FHWA), 1998)	**100**	natural aggregates	NA	NA	18-19	5.7-7.5	NA	30-42
	50		NA	NA	NA	NA	42-125	NA
	15		NA	NA	NA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

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

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



(a)



(b)

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