RECYCLED AGGREGATES USED IN ROAD LAYER AS AN ENVIRONMENTAL SOLUTION

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ABSTRACT

The road network in Québec represents 164 000 km of roads for a number of vehicles that has doubled over the past two years reaching about 4 million. This traffic and the load increase on the road network have accelerated the deterioration of roads (Pillon et Laquerre, 1999). For budgetary and logistical considerations as well as in order to integrate sustainable development in road infrastructure, recycled granular materials (MR) could be used, in part or in whole, in the new road infrastructures which will be built, rebuilt or rehabilitated. The term «recycled granular materials» involves three types of granular materials (0-20 mm) which are natural aggregates, levelled and crushed asphalt and crushed cement concrete. With the actual scientific knowledge about the MR, these materials can not easily be used. Thus, it is important and urgent to know the properties of MR in order to use them on site as a base or sub-base pavement layers and therefore reduce their environmental and economic impact.

A complete geotechnical characterization of MR is presented. The thermal behaviour of MR in a northern climate is described using results from tests of frost susceptibility. Moreover, the mechanical behaviour of MR is determined by the resilient modulus. The determination of this modulus allows us to provide the stress conditions of road materials. Finally, the evaluation of the hydraulic conductivity by the permeability test predicts the MR behaviour in different conditions of saturation.

The overall results provide a clearer view of the mechanical, hydraulic and thermal behaviour of MR and thus confirm the relevance of using MR as road base or sub-base materials. Moreover, the properties determined for the MR in this study will help engineers to use real values for parameters in road design, rehabilitation or maintenance.

Keywords: recycled granular materials, aggregates, geotechnical characterization, mechanical behaviour, hydraulic behaviour, thermal behaviour

INTRODUCTION

Québec (Canada) currently realizes extensive road works because it is necessary to modernize the road network that is more than 30 years old. However, in each worksite, massive amounts of materials are generated. That is why it is really important to reuse in place all these materials for the road construction or rehabilitation in order to develop sustainable infrastructures with financial and logistic considerations.

The possibility that some of these materials can be reused in a road structure, in accordance with current standards, has already been considered. This possibility is well documented with research studies from, among others, U.S. (Robinson Jr. *et al.*, 2004), Spain (Vegas *et al.*, 2008,) and South Korea (Park , 2003).

Following the first research done on the recycled granular materials (MR) by the *Ministère des transports du Québec* (MTQ), a functional classification was proposed for the MR (Marquis *et al.* , 1998). This MR classification has been developed based on the proportion of three source materials : natural aggregate (GN), cement concrete (BC), and bituminous concrete (EB). European countries have also developed classifications for the MR as Belgium (Organisme Impartial de Contrôle de Produits pour la Construction, 2003) and France (Direction Régionale de l'Équipement d'Île-de-France, 2003). Nevertheless, the MR properties were little known. In this context, the present research project aims to characterize the classified MR.

RESEARCH PROGRAM

RESEARCH SIGNIFICANCE AND OBJECTIVE

The classified MR (type 2 to 6, non-stabilized) have been characterized and compared to a «standard» granular material (MG-20). In order to well know the MR properties, a geotechnical characterization has been carried out. Moreover, to explore these properties, a study of MR mechanical, hydraulic and thermal behaviour was also carried out. The ultimate goal of this study is to know the MR real characteristics in order to possibly use them on site as a base or sub-base pavement layers.

MATERIALS

The studied MR consist of three source materials which are a granitic gneiss for the natural aggregate, levelling residues for the bituminous concrete, and a crushed concrete for cement concrete. The different MR (type 2 to 6) were obtained by mixing together the three source materials. Table1 and Figure 1 show the MR formulations. On Figure2, red points indicate the studied MR in the triangle classification of the MTQ.

Table 1 Formulations of MR studied

%	MR2	MR3	MR4	MR5	MR6
GN	7,5	70	33	50	25
BC	80	-	33	-	-
EB	12,5	30	33	50	75

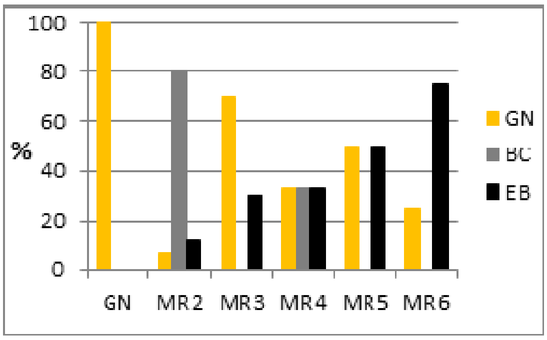

Figure 1 Formulations of MR studied

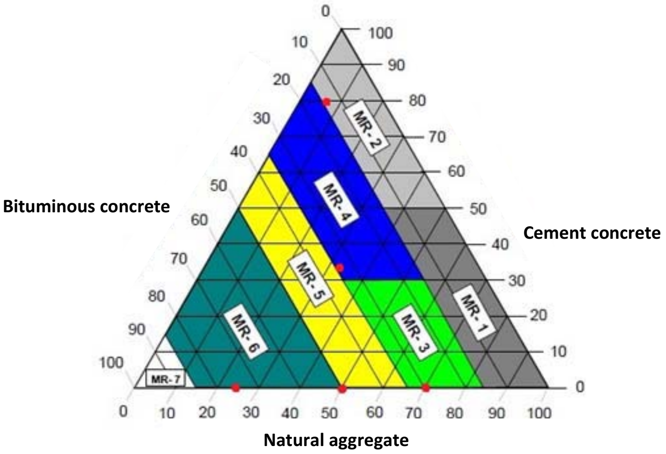

Figure 2 MR studied (red points) in the triangle classification of MTQ

GEOTECHNICAL CHARACTERIZATION

Particle-size analysis by screening

The particle-size analysis by screening were carried out according to BNQ 2560-040 standard. Figures 3 and 4 show the different grain-size distributions of the three source-materials (GN, EB and BC) and of the studied MR. On each figure, the black curves correspond to the top and bottom curves of the MTQ grading zone.

Although some materials have fine particles content smaller than that of the below curve of the MTQ grading zone, the particle-size analysis of the studied MR are similar to that of a standard MG-20. Moreover, most materials have open grading.

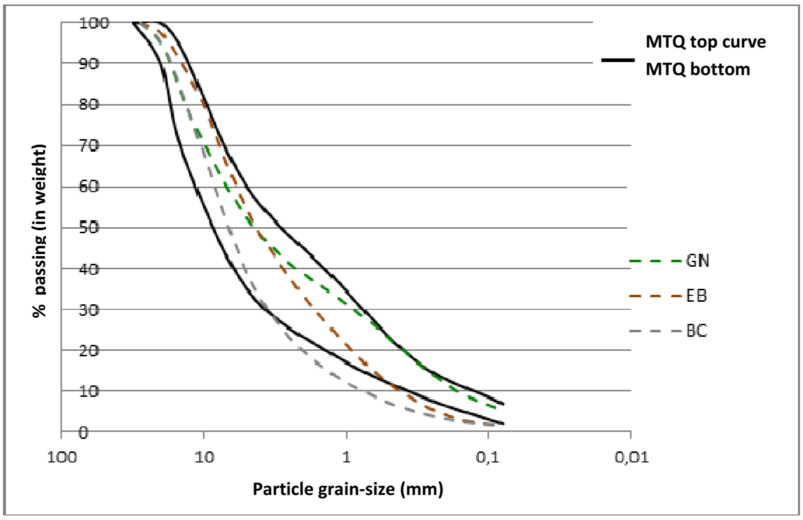

Figure 3 Grain-size distributions of the three source-materials (GN, EB and BC)

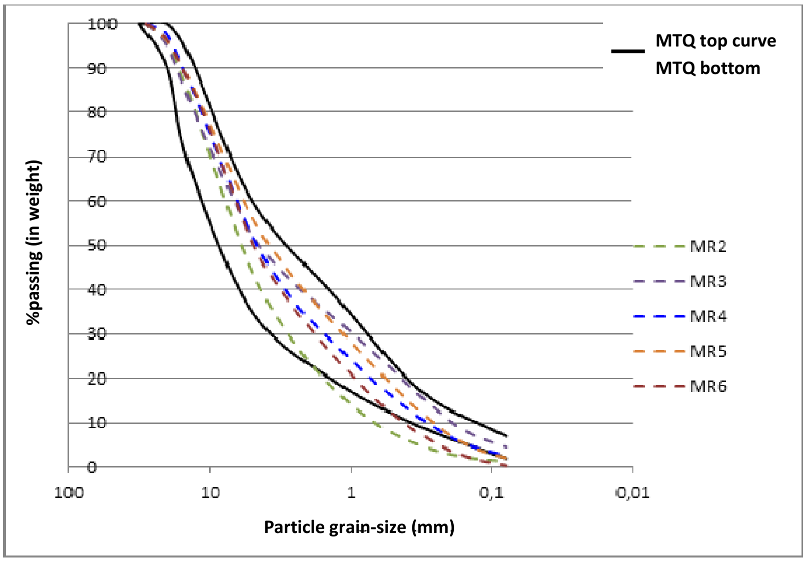

Figure 4 Grain-size distributions of the studied MR (type 2 to 6)

Density and absorption of coarse aggregates and fine aggregates

The density and absorption tests of coarse aggregates and fine aggregates were carried out according to LC 21-065 and LC 21-067 standards. Table 2 gives the density and absorption values for the different materials. The values of Table 2 show that the values of densities are close to each other for all the materials. The GN (granitic gneiss) show the highest density but the lowest absportion.

In both cases, either the MR containing bituminous concrete and MR containing cement concrete, the absorption values increase with the percentage of source-material contained in the MR. The MR containing cement concrete have highest absorption percentages due to the presence of the cement matrix and therefore a larger specific surface.

Table 2 Density and absorption values of coarse aggregates and fine aggregates of MR studied

Granular material	Coarse aggregates				Fine aggregates			
	D_{bulk}	D_{bulk}	$D_{apparent}$	$\%_{absorption}$	D_{brute}	D_{bulk}	$D_{apparent}$	$\%_{absorption}$
GN	2,63	2,65	2,69	0,81	2,64	2,66	2,69	0,84
EB	2,27	2,33	2,41	2,48	2,31	2,35	2,40	1,55
BC	2,28	2,40	2,59	5,23	2,24	2,40	2,65	6,80
MR2	2,24	2,31	2,41	3,26	2,43	2,49	2,57	2,25
MR3	2,47	2,50	2,55	1,28	2,53	2,56	2,60	1,08
MR4	2,35	2,42	2,53	3,00	2,52	2,54	2,58	0,92
MR5	2,41	2,45	2,53	1,98	2,42	2,46	2,52	1,69
MR6	2,37	2,42	2,48	1,89	2,40	2,42	2,45	0,83

Abrasion resistance

Table 3 show the percentage loss by abrasion values for each material studied.

Table 3 Abrasion resistance values of MR studied

Granular material	Abrasion (%)
GN	41,2
EB	32,5
BC	44,3
MR2	34,3
MR3	37,1
MR4	34,3
MR5	35,1
MR6	33,2

Requirements of the MTQ (NQ 2560-600) standard for a MG-20 standard limits percentage loss by abrasion to 50%. The results of Table 3 show that all materials studied meet the MTQ requirement for a use in pavement base layer. The two source-materials, the natural aggregate and the cement concrete have higher percentage loss by abrasion than other materials. The abrasion resistance values for all granular materials indicate that these materials could withstand greater stresses without any change to their grading.

Attrition wear coefficient

Determining the attrition wear coefficient is a measure of aggregate resistance to friction wear in presence of water. The results of attrition wear coefficients for each granular material are given in Table 4. Requirement of the MTQ (NQ 2560-600) for an MG-20 is an attrition wear percentage ≤ 25%. The natural aggregate (granitic gneiss) is by far the most resistant material to attrition wear. The aggregate hardness is a parameter that should not be overlooked when designing a road because a change of grading by grain crushing may have consequences which must be taken into account to try to ensure the similarity of grading before and after construction activities. Indeed, during a road construction, the attrition caused by heavy vehicles and the wear caused by tire action on aggregate surfaces can change the granular material grading curve by fine particle production. That is why it is important that all the materials studied meet the MTQ attrition wear requirement.

Table 4 Attrition wear coefficients of MR studied

Granular material	Attrition wear coefficient (%)
GN	7,55
EB	23,60
BC	21,16
MR2	16,44
MR3	12,70
MR4	14,95
MR5	14,35
MR6	22,86

Density and optimum water content

Table 5 gives the optimum water content and dry density corresponding to each material.

Table 5 Density and optimum water content of MR studied

Granular material	w_{opt} (%)	ρ_d (kg/m^3)
GN	5,1	2200
EB	3,7	1922
BC	7,1	1856
MR2	6,6	1884
MR3	5,3	2149
MR4	5,6	1971
MR5	4,3	2107
MR6	4,0	2009

From the grading curves and Table 5, it is clear that a granular material with a higher fine content requires a greater amount of water to reach the optimum Proctor value. This is explained by the increase of specific surface due to a larger amount of fine particles.

Bearing capacity

Figure 5 show the bearing capacity results for each of granular materials studied. From Figure 5, it is clear that the force recorded for GN (granitic gneiss) is much higher than that for the other materials. This result could certainly be explained by a optimized granular skeleton (greater granular packing) for the GN.

The source of the material greatly influences how the aggregates will be organized in the sample. This bearing capacity test provides an overview of the mechanical behavior of the MR used as pavement base layer.

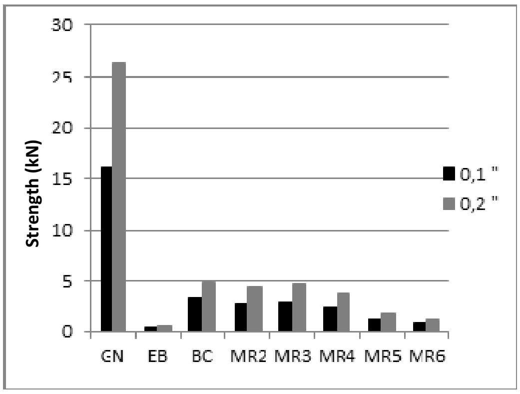

Figure 5 Bearing capacity results of the studied MR (type 2 to 6)

BEHAVIOUR STUDY

Using the geotechnical characterization results obtained, it becomes interesting to conduct further tests on MR to assess their mechanical, hydraulic and thermal behavior.

Resilient modulus

The granular materials behave as a nonlinear elastic-plastic material. Granular materials are considered homogeneous and isotropic to simplify the result analysis the pavement design. The mechanical behavior is assessed by the resilient modulus M_r. The resilient modulus of a material is a measure of its rigidity. This concept is expressed in a pavement structure by how the base layer transfers and disperses the load within the pavement structure.

Figure 6 illustrates the nonlinear elastic-plastic behavior of the material and shows that, for a given stress, most of the strain is elastic (reversible) and the plastic strain (permanent and non reversible) increases under the action of a repeated load.

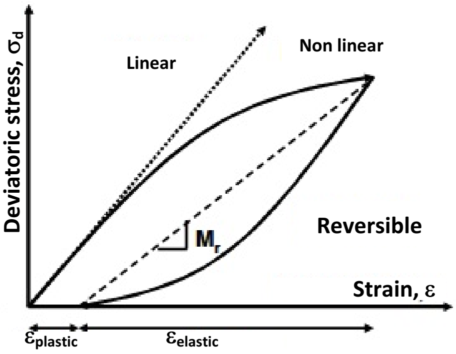

Figure 6 Reversible behaviour of granular material

The purpose of the repeated load triaxial test as described in the LC 22-400 standard is to determine the resilient modulus M_r for a sample of granular material. To remove a maximum of permanent strain in order to only analyze the elastic behavior of the material, it is necessary to condition the sample for 10 000 cycles at a frequency of 10Hz (loading time of 0.1 sec and rest of 0.9 sec) by applying confining stress (σ_3) and deviatoric stress(σ_d) of 105 kPa. To determine the nonlinear relationship of the resilient modulus, M_r are obtained at three different water contents: in the initial state, in the saturated state, in the drained state. Then they are characterized at the 15 stress states mentioned in the AASHTO T307 standard. Table 6 shows the results of all MR at a stress state of σ_3 = 70 kPa and σ_d = 140 kPa because this is an intermediate stress state.

Table 6 Resilient modulus of MR studied

Granular material	initial	saturated	drained
	M_r (MPa)	M_r (MPa)	M_r (MPa)
GN	415	357	378
BC	432	460	451
MR2	449	509	487
MR3	354	297	299
MR4	368	318	310
MR5	295	278	293
MR6	393	355	350

The results presented in Table 6 clearly show that the values of M_r at the initial water content are higher than those obtained at the saturated and drained water contents which are similar. The MR2 and BC have higher values of M_r (respectively 449 and 432 MPa at the initial water content) than the other MR. MR containing bituminous concrete have M_r values which decrease with the increase of the EB proportion. At the initial water content, in comparison with the natural aggregate (415 MPa), the MR3, MR4, and MR5 have a M_r which decreases by about 15% (354 MPa), 11% (368 MPa) and 29% (295 MPa) respectively. The case of MR6 is unusual even if the value of its M_r is high (393 MPa at the initial water content). Indeed, beyond a certain EB proportion, conditioning procedure has to be extended to minimize permanent strain before the starting of the repeated load triaxial test because a kind of post compaction occurs. This phenomenon could not be compensated for 100% EB sample even with a longer conditioning procedure. This may suggest a different procedure should be used to adequately assess the mechanical behavior of MR containing more than 75% of EB.

Figures 7 and 8 show the relation between the resilient modulus and the total stress for each material at the saturated state and after the conditioning procedure. Figure 7 shows much higher resilient modulus values for the MR2 and the BC due to the high rigidity of the cement concrete. For the MR3 and MR4, resilient modulus values are rather similar.

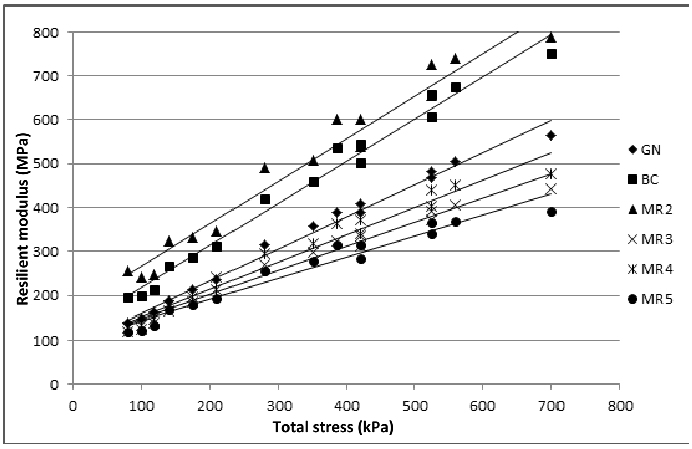

Figure 7 Resilient modulus of MR studied at the saturated state

MR5 is special case because, from a certain EB proportion, the sample accumulates more permanent strains that influences the result. Figure 8 corresponds to tests with the MR5 and MR6 by applying a conditioning 30 000 cycles followed by additional conditioning of 10,000 cycles to minimize permanent strains.

In summary, the repeated load triaxial test reproduces best the real mechanical solicitation of a granular material in a pavement structure. These tests show that most of the MR have lower resilient modulus than the MG-20 standard.

However, this does not exclude their possible use in a pavement base layer because an adjustment of the thickness of the base layer or the surface layer could be done in the pavement design.

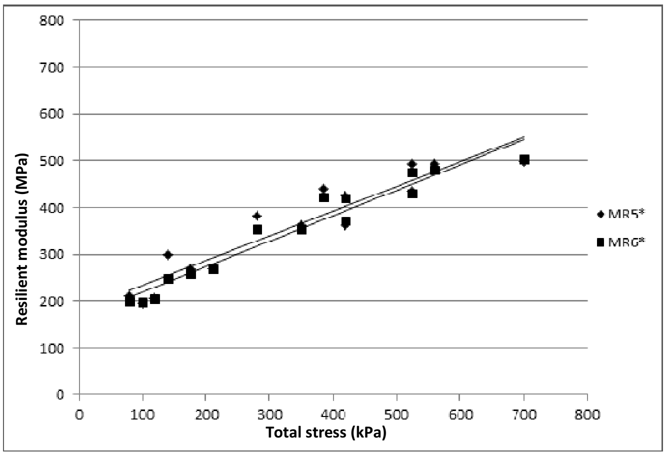

Figure 8 Resilient modulus of MR5 and MR6 studied at the saturated state

Permeability

The permeability test aims to determine the hydraulic conductivity of sand, gravel or coarse granular material at determined water contents and Proctor energy levels. The test is performed at constant load. The permeability coefficient *k* is obtained using Darcy's law because the flow regime in the sample is slow and laminar.

Table 6 presents the permeability coefficient values calculated from the results obtained from the permeability test for each granular material.

It is difficult to measure side effects caused by the use of rigid permeameter. However, side effects are negligible on the measurement of hydraulic conductivity which explains why this type of permeameter is still frequently used. Smaller proportion of fine particles (EB and BC) cause an increase of permeability. In fact, a smaller proportion of fine particles causes a decrease of the specific surface and an increase of voids in the sample which promotes the water flow.

All recycled granular materials are permeable (> 1 x 10-7 cm / s) and the increase of the EB proportion increases the permeability of the sample.

Table 6 Permeability coefficient of MR studied

Granular material	*k* (cm/s)	% fines
GN	2,41 x 10^{-4}	5,44
EB	1,10 x 10^{-2}	1,46
BC	2,04 x 10^{-2}	1,47
MR2	1,57 x 10^{-2}	1,31
MR3	2,13 x 10^{-4}	4,51
MR4	2,27 x 10^{-2}	2,68
MR5	9,67 x 10^{-4}	2,02
MR6	2,37 x 10^{-3}	0,36

Frost susceptibility

The frost susceptibility test aims to assess the segregation potential (SP) for granular materials. This test is based on the concept of segregation potential developed by Konrad and Morgenstern (1980). The SP is defined as the ratio between the flow velocity of the interstitial water to the freezing front and the thermal gradient in the material.

Table 7 gives the segregation potential values calculated from the results obtained from the frost susceptibility test and the fine particle content for all the materials studied.

Table 7 Segregation potential and fine particle content of MR studied

Granular material	SP (mm²/°C.jour)	% fines
GN	5,12	5,44
EB	2,20	1,46
BC	4,77	1,47
MR2	5,56	1,31
MR3	2,97	4,51
MR4	2,97	2,68
MR5	5,57	2,02
MR6	2,09	0,36

The MTQ requirement for a granular material to be considered non-frost susceptible is a segregation potential lower than 12 mm² / °C.jour (Labrie, 2002). The results obtained for all MR confirm their non-frost susceptibility.

CONCLUSIONS

The mechanical behavior of the recycled granular materials was evaluated by determining the resilient modulus. After analyzing the results it is possible to group the materials in three categories. The first category groups together the crushed concrete (BC) and the MR2 with M_r values higher than other materials because of the high stiffness of the concrete. The second category groups the two particular cases, MR5 and MR6. If these materials would be used in pavement base layer, it becomes important to apply a pre-compaction in order to eliminate the maximum of the permanent strain to achieve the desired properties and optimize the sustainability of the road. The third category groups the other MR which are GN, MR3 and MR4. The case of GN corresponds to the standard case because the use of granitic gneiss as MG-20 in road base layer is already widespread and its properties and behavior are well known. In regard to MR3 and MR4, they have mechanical properties slightly weaker than the GN. Although they have a weaker M_r values, they have good rigidity.

The hydraulic conductivity values obtained show all that the MR are permeable. Moreover, the results obtained from laboratory tests show that all of them are frost-resistant.

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