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The impact of grain crushing on road performance

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Abstract

This paper presents the results of a study of grain crushing in road construction and its effect on road behaviour. Sieve analyses of field samples confirmed that grain crushing occurs during compaction of the base layer despite the good quality of aggregates used. Laboratory testing indicated that grain crushing reduces the resilient modulus of the aggregate material by half and increases the permanent deformations by one to three fold depending on the state of density and stresses considered. Road design and analyses undertaken to delineate the effect of grain crushing on performance showed that particle breakage yields a significant increase in rutting and longitudinal and alligator cracking of roads.

Keywords Aggregates, alligator cracking, base layer, grain crushing, longitudinal cracking, permanent deformation, resilient modulus, rutting.

1. Introduction

Pavements are complex structures constructed with materials that vary in their nature and properties. Pavements rarely reach their projected full design life, and some fail badly a few years after being opened to traffic. The perplexity of pavement performance has persisted despite all the advances in the design and analyses of road structures in the last 40 years. These advances covered many aspects including the shift toward mechanistic material characterization schemes and the development of a variety of design and analysis models with different capabilities and idealizations of road structures. The adoption of the resilient and complex modulus concepts to characterize unbound and asphalt concrete materials and the emergence of mechanistic-empirical pavement design guides are good indicators of the enormous efforts deployed recently to better comprehend the behaviour of roads and improve the practice of pavement engineering.

The increasing incidence of the premature development of road distresses has led to new approaches examining mechanisms that were missed or ignored in the past. Grain crushing emerged as an overlooked factor with the potential of explaining some of the discrepancies between expected (as designed) and in-service road performance. Knowing, for example, that gradation plays an important role in the resilient behaviour of granular base materials (Tian et al., 1998; Zeghal, 2000), it was expected that significant grain crushing (gradation alteration) would affect the properties of granular materials.

During road construction, it was observed that aggregate materials laid in base layers were crushed during compaction. In some instances, the surface of the compacted layer gave the impression that the material was composed of small and fine aggregates though it contained aggregates as big as 19 mm. These field observations generated interest in grain crushing and, consequently, an investigation was launched to answer questions related to the extent of field crushing and its effect on material properties and road performance.

This paper, investigates grain crushing using laboratory-testing of field samples. In Section 2, grain crushing studies are reviewed. Section 3 presents analyses of field samples to establish the existence and extent of field grain crushing. Section 4, describes the experimental testing program, and Sections 5 and 6, examine the impact of grain breakage on the mechanistic properties of aggregate materials and on road performance.

2. Grain crushing studies

Although grain crushing of aggregates has been recognized since the early years of the 20th century, it was not considered an important phenomenon in engineering construction until the late 1950s when the personnel of the U.S. Army Engineer Division observed a degradation of base course materials during construction (Aughenbaugh et al., 1966).

In the 1960s, several studies on grain crushing were undertaken. Vesic and Barksdale (1963) performed drained triaxial tests on sand at a variety of confining pressures and observed that grain crushing increases as the confining pressure increases. Aughenbaugh et al. (1966) investigated grain crushing during field compaction and concluded that the greatest grain breakdown occurs during the first compactor pass and in the top layer, and the amount of crushing decreases with the number of passes and depth. Marsal (1966) concluded that coarse materials crushed more than fine materials based on drained triaxial tests performed on coarse gravels and broken rocks up to 20 cm in diameter. Lee and Seed (1966) observed a considerable amount of crushing in fine sand, which increased with the increase in the confining pressure. Lee and Farhoomand (1967) concluded that grain crushing is a general feature of all granular materials. In summary, the results of the 1960s studies concluded that the amount of breakage increases with the increase in grain size of uniform soil, angularity of particles, confining pressure and shear stress at one confining pressure.

In 1973, Marsal found that fragmentation in a material starts when the stress level exceeds 1.6 MPa but decreases as the stress exceeds 2.5 MPa due to the fact that grain crushing causes the material to compact and become much denser with more contact points between the particles. Lambe and Whitman (1979) fine-tuned these results when they established that breakage usually starts to take place at stresses exceeding 3.5 MPa for fine-grained soils and at stresses as low as 700 kPa for coarse-grained or uniformly distributed materials.

In 1981, Holtz and Kovacs focussed on the load transmitted during field compaction. They concluded that the ground contact pressure is a function of the type of equipment used and can be in the range of 0.4 to 7.0 MPa. Forssblad (1981) estimated the static linear load to be 2.5 MPa under rollers with a 10 ton static drum weight. He also added that if the roller vibrates, the stress wave pulse generated by vibration should be added to the static weight of the roller. The dynamic part is frequency dependent and can be approximately 10% of the static pressure. In 1985, Hardin used the results of a series of experimental tests to show that strength and compressibility of soil elements are strongly affected by the amount of grain crushing during loading and deformation. He related grain crushability to grain size distribution, void ratio, water content, and shape and hardness of the individual particles.

In the 1990s, more studies on grain crushing confirmed earlier findings. They demonstrated that granular materials, forming part of engineering structures, such as the base of a flexible pavement, highway embankments and foundations, are subjected to either static or dynamic loads and, consequently, they sustain particle abrasion and particle breakage (Lade et al., 1996; Coop, 1999; Raymond, 2000).

The interest in grain crushing continues. In 2001, Lowery and Zeghal simulated construction conditions of aggregate materials in the field (small projects) using a vibrating plate and compared them to those used in the laboratory during sample preparations (hand-held vibrating hammer). They pointed to grain crushing to explain the observed difference between the grain size distribution of samples prepared in field-simulated conditions and those prepared in the laboratory. In 2002, Zeghal and Edil analyzed quartz material (sand) from a modified direct shear test to reveal a close relationship between grain crushing and the work dissipated plastically during shear. They used this relationship to incorporate the effect of grain crushing in the model they developed to study soil-structure interaction problems.

In the last decade or so, there has been great interest in modelling grain crushing analytically. In 1999, Bolton presented his view on the role of micro-mechanics in soil mechanics. He concluded that continuum soil mechanics is insufficient, and there is a need to monitor the evolution of micro-structure during soil tests, especially the increase in specific surface or the reduction of permeability either of which would indicate crushing and void filling. He suggested that observations of the changing micro-structure of soils would permit the selection and refinement of relevant micro-mechanisms, which control soil behaviour. In 2001, Jensen et al. numerically modelled the damage to particles using the clustering technique in discrete element modelling. They showed that the degree of damage is related to the angularity of the clusters. Applying the developed model, to study the impact of particle damage on interface behaviour, they concluded that a very distinct shear zone is evident when particle damage is considered, and this occurs without significant reduction in the maximum shear strength of the medium. Cheng et al. (2004) simulated stress-path tests on triaxial elements comprising crushable agglomerates. They showed that the plastic behaviour of the numerically generated soil closely resembles that of real sand.

3. Characterization of grain crushing observed in the field

Two types of samples were taken from a road construction site. The samples of the first type were acquired directly from the stockpile of the aggregate material intended for the construction of the base layer and are referred to as the original material. The samples of the second type were taken from the base layer after compaction using a 10-ton steel roller and are referred to as crushed or compacted material. Several samples were taken after delivery by different trucks and at different locations of the compacted base course to ensure that samples taken to the laboratory are consistent and representative of the materials. The material investigated is a typical granular material usually used in base layers and satisfies the gradation requirements of the Ministry of Transportation of Ontario (MTO) for the granular A type. It consisted of crushed rock composed of hard, uncoated, fractured fragments produced from rock formations of uniform quality as indicated in the Ontario Provincial Standards for Roads and Municipal Services (OPS). Data obtained from the material producer confirmed the good quality of the aggregates produced and delivered to the site. Figs. 1 and 2 presenting the results of the Micro-Deval test for the coarse (ASTM D 6928-06) and fine (CSA A23.2-A23-04) fractions, respectively show that both these fractions are made of hard aggregates with good resistance to abrasion. The mean abrasion loss of the coarse fraction was 19.0% (Fig. 1), which is lower than the maximum Micro-Deval abrasion loss (25%) recommended, in ASTM standard D 6928-06, for granular base course materials. Further, the mean abrasion loss of fine fraction was 21.4% (Fig. 2).

In the laboratory, the collected samples were subjected to sieve analyses to confirm and quantify grain crushing observed in the field. The results presented in Fig. 3 show that the gradation of the original material did not exactly conform to the requirements of MTO as the percent passing the 75μm sieve fell outside the required limits. It also confirmed that the gradation of the original material was altered with compaction. Further, Fig. 4, presenting the percent retained for the two types of materials, indicates the following results.

- ❑ The largest particles (bigger than 19 mm) showed almost no crushing.
- ❑ The percentage of particles retained on the 9.5 mm and 4.75 mm sieves decreased by 22% (from 31% to 24%) and 15% (from 26% to 22%), respectively.
- ❑ The percentage of particles retained on the 0.297 mm and 0.075 mm sieves experienced an increase in the percent retained of 88% (from 8% to 15%) and 33% (from 6% to 8%), respectively.

4. Experimental program

The experimental program was designed with the objective of investigating the effect of grain crushing occurring during compaction in road construction. It aimed at characterizing (mechanistically) the original and crushed materials. The resilient modulus and permanent deformations of the original material were compared to those of the crushed material to delineate the impact the gradation alteration has on the behaviour of aggregate materials.

4.1 Laboratory testing scheme

The testing scheme used in this study was recently developed at the National Research Council Canada (Khogali and ElHussein, 2004). The test, named M_r–PD, goes beyond the conventional method of determining the resilient modulus (M_r) by concurrently measuring the percentage permanent deformation (PD) that the material experiences under dynamic loading.

The testing system consists of:

- ❑ a triaxial pressure chamber, used to house the test specimen and maintain the confining pressure;
- ❑ an MTS 810 loading frame, used to apply the deviator load;

- an assembly of axial and radial deformation measuring sensors, contained within the triaxial chamber;
- a load cell placed on top of the test specimen for measuring the axial repetitive load;
- a pressure manifold and regulator for applying the confining pressure; and
- an MTS data acquisition system, to collect load and deformation signals generated during the test. A complete description of the system can be found in a special publication of the National Research Council Canada (2004).

A material to be tested is initially air dried and thoroughly mixed. Then, a mechanical sample splitter is used, as per AASHTO designation T248 – 95, to reduce the sample to the desired weight needed for the specimen preparation. Later, the material is spread over a tray and oven dried at 110^0C for 24 hours.

When preparing samples, a rubber membrane is placed inside a 300 mm split compaction mould. The granular material, mixed with the required amount of water, is placed in the mould in eight lifts. Each lift is compacted to produce a lift thickness of 37.5 mm. The final specimen, 150 mm in diameter and 300 mm in height, is placed inside the triaxial chamber, and two linear variable differential transducers (LVDT) are internally mounted to measure axial deformations.

In the M_r–PD test, samples are subjected to a repetitive haversine load. Each cycle consists of applying the repetitive stress for a period of 0.1 second, followed by a rest period of 0.9 second. The applied load and the resulting deformations are monitoring for all loading cycles.

4.2 Testing matrix

The experimental investigation consisted of testing the original and crushed materials at their optimum moisture content but at different degrees of compaction and deviator stresses. Two densities (95% and 90% of the maximum modified Proctor density) and two deviator stresses (50 and 80 kPa) were considered. The deviator stresses were chosen to reflect the level of stresses measured in the field for different road structures and materials. In the case of samples tested at 90% of their maximum modified Proctor density (MMPD), only a deviator stress of 50 kPa was used since the samples did not endure the stress level of 80 kPa and failed. The confining pressure was kept constant at 50 kPa for all tests, and a minimum of two replicates was used in each test.

5. Effect of grain crushing on the behaviour of aggregate materials

The results of M_r–PD tests performed on the original and crushed materials at different conditions were analyzed and compared to determine the impact of grain crushing on the resilient modulus and permanent deformations.

5.1 Impact on the resilient modulus

The resilient modulus was evaluated at each loading cycle. Fig. 5, presenting a typical variation of the resilient modulus with loading cycles, suggests that the resilient modulus displays variations before it stabilizes. The stabilized resilient modulus is the one considered in this study. Resilient moduli of the original and crushed materials were first examined to delineate the effect of density and stress on these materials. Table 1, presenting the results of all tests undertaken, shows that both materials exhibited similar trends. At the same level of deviator stress (50 kPa), an increase in density from 90% to 95% MMPD resulted in an increase in the resilient modulus. The increase was about 57% and 51% for the original and crushed materials, respectively. These findings are more in agreement with the results reported by some early studies (Hicks, 1970; Robinson, 1974; Rada and Witczak, 1981) than with those reported by more recent studies (Thom and Brown, 1988; Brown and Selig, 1991). The latter investigations concluded that density has a relatively insignificant effect on the resilient modulus.

At the same level of density (95% MMPD), an increase in the deviator stress from 50 kPa to 80 kPa resulted in an increase of 26% and 34% in the resilient modulus of the original and crushed materials, respectively. Both materials are sensitive to the level of deviator stress, which contradicts the results of Hicks (1970) who observed that the deviator stress has almost no effect on the resilient modulus. However, the findings confirm the results of Brown (1974) who reported a significant effect of the deviator stress on the resilient behaviour of aggregate materials especially at high levels of stress.

Though the original and crushed materials exhibited similar trends related to the effect of density and deviator stress, they showed totally different resilient behaviours. Due to crushing and thus gradation alteration, the original material displayed a degradation of its resilient characteristics. At all conditions of density and deviator stress, a decrease of 46% to 49% in the resilient modulus was observed.

5.2 Impact on permanent deformations

The permanent deformations data were also first examined for each individual material to delineate the effect of different factors. The results are shown in Figs. 6 and 7 for the original and crushed materials, respectively. For the original material, at a deviator stress of 80 kPa, decreasing the density from 95% MMPD to 90% MMPD resulted in approximately a seven-fold increase in permanent deformations (Fig. 6). Further, at a density of 95% MMPD, the original material showed a little more than a two-fold increase in permanent deformations when the deviator stress was increased from 50 kPa to 80 kPa. For the crushed material, the effect of density on permanent deformations is lower than the effect seen in the case of the original material; a three-fold increase in permanent deformations was observed when density passed from 95% MMPD to 90% MMPD (Fig. 7). The results also suggested that the crushed material is less sensitive than the original material to the level of deviator stress. Increasing the deviator stress from 50 kPa to 80 kPa resulted in an increase of only 15% in permanent deformations. The contrast between permanent deformations of the original and crushed materials for different conditions is shown in Figs. 8 to 10. Fig. 8 presents the comparison at a density of 95% MMPD and a deviator stress of 80 kPa. It shows that the crushed material experienced an increase in permanent deformation of about 113% with respect to the original material. At a density of 90% MMPD and a deviator stress of 50 kPa, the increase in permanent deformations (that the crushed materials exhibited with respect to the original material) was 139% as shown in Fig. 9. At a density of 95% MMPD and a deviator stress of 50 kPa, the crushed material showed an increase of 291% in permanent deformations with respect to the original material (Fig. 10).

6. Impact of grain crushing on performance

Though the experimental program showed that grain crushing occurs during compaction of granular base course materials and that the gradation alteration results in a clear degradation of the mechanistic properties, it is interesting to assess the impact this degradation has on the performance of roads. To achieve this objective, two road structures were considered. They had the same surface, subbase and subgrade materials but different base materials. The base course of the first and second structure was made of the original and crushed material, respectively (Fig. 11). The surface layer consisted of an asphalt concrete (known as HL 3) commonly used in Ontario, Canada. Similar input values related to all other variables (traffic, environment, etc.) were used in the analyses. The analyses focussed on the effect of grain crushing on rutting of the base layer and also on the overall road performance in terms of total rutting, surface-down cracking (longitudinal) and bottom-up (alligator) cracking.

Fig. 12 compares the rutting of the base layers constructed with the original and crushed materials. The use of the original material properties in the design resulted in an under-estimation of the real base rutting (resulting from the use of the crushed material properties) by 35% after 20 years of service. This effect was also apparent on the overall road rutting (Fig. 13). Performing design and analysis using the original material might mask the potential of excessive rutting exceeding the design limit (fixed to 19 mm for this example) and give a false sense of good performance. The use of the original material showed that the design limit would be reached only a few months before the end of the design life of 20 years. However, the use of the crushed material indicated that the design limit would be reached about six years earlier.

The impact of grain crushing on two other performance criteria was also investigated. The effect on longitudinal cracking is shown in Fig. 14. Though both the original and crushed materials resulted in longitudinal cracking below the fixed design limit of 190 m/km, they exhibited significantly different behaviours in terms of the magnitude and rate of distress. Fig. 14 shows that the crushed material resulted in longitudinal cracking that is about 4.7 times that obtained when the original material was used at the end of the design life. Further, the rate of development of longitudinal cracking for the crushed material structure was higher than that developed for the original material structure at any pavement age. Specifically, this rate in the last four years of the design life was about 3.8% and 1.1% for the road structure constructed with the crushed and original material, respectively. The effect of grain crushing on the alligator cracking is presented in Fig. 15. The results showed a trend similar to that seen with the longitudinal cracking. At the end of the design life, the crushed material yielded alligator cracking that is about 2.5 times that obtained when the original material was used. Further, the rate of development of alligator cracking was higher in the case of crushed material and more pronounced toward the end of the design life.

7. Conclusions

Several previous studies of granular materials concluded that grain crushing is a feature of all soils. This finding, along with field observations suggesting that granular materials used in the base layer of a pavement crush during compaction with a 10-ton steel roller generated interest in particle breakage. The investigation launched to study this phenomenon and its effect on material properties and road performance made use of laboratory testing and analytical tools. The results of this investigation and recommendations are summarized below.

- ❑ Field samples of a granular material used in the base layer of a new road construction were taken before and after compaction using a 10-ton steel roller.
- ❑ Micro-Deval abrasion tests illustrated the good quality of sampled aggregates. The mean abrasion loss of coarse fraction was lower than the maximum recommended in the ASTM standard D 6928-06, for granular base course materials.
- ❑ Sieve analysis of field samples indicated that the granular material crushed during compaction despite the good quality of the aggregates. It was found that particles larger than 4.75 mm crushed and that the amount of crushing was higher for larger particles. The degradation of large particles resulted in an increase in the amount of particles smaller then 0.297 mm.
- ❑ Laboratory testing of field samples indicated that grain crushing altered both the resilient and permanent deformation behaviours of the material. Particle breakage resulted in a decrease of almost 50% in the resilient modulus of the material and an increase of 113% to 291% (depending on the state of density and stresses considered) in its permanent deformations.

- ☐ Road design and analyses suggested that grain crushing yielded an increase in the rutting of the base layer and the whole road. Designing a road without taking into account particle breakage might translate into excessive rutting and a need for rehabilitation almost six years earlier than what is called for by the design. Further, ignoring grain crushing resulted in an under-estimation of the road longitudinal and alligator cracking in terms of magnitude and rate of development.
- ☐ Based on its observed impact on the properties of the material and road performance, it is recommended that grain crushing be taken into account in the design of roads.

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List of figures

Table 1 Impact of grain crushing on the resilient modulus

Aggregate type	Resilient modulus (MPa)		
	Density (95% MMPD[a])		Density (90% MMPD)
	Deviator stress (80 kPa)	Deviator stress (50 kPa)	Deviator stress (50 kPa)
Original (before compaction)	402	320	204
Crushed (after compaction)	218	163	108

[a] Maximum modified Proctor density

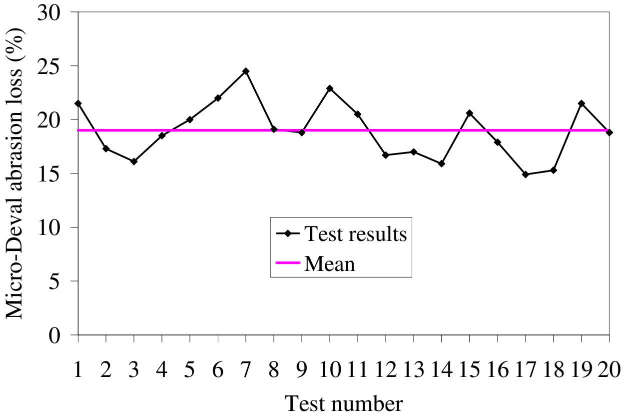

Fig. 1 Micro-Deval results for coarse fraction

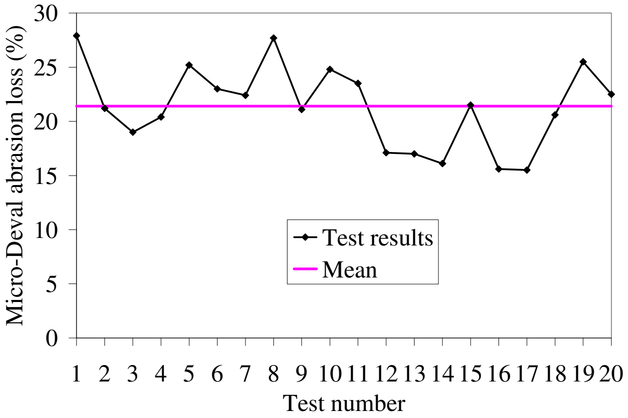

Fig. 2 Micro-Deval results for fine fraction

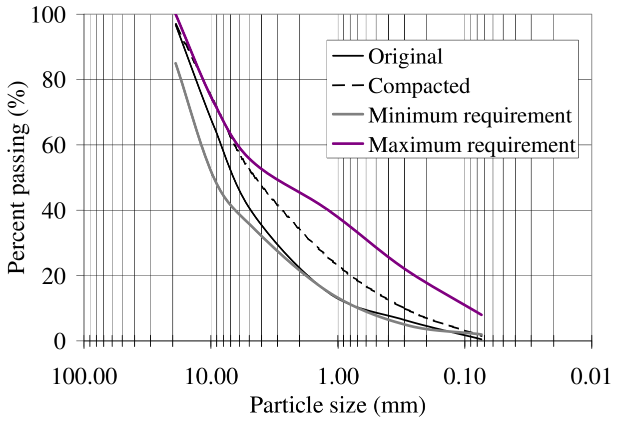

Fig. 3 Alteration of gradation with compaction

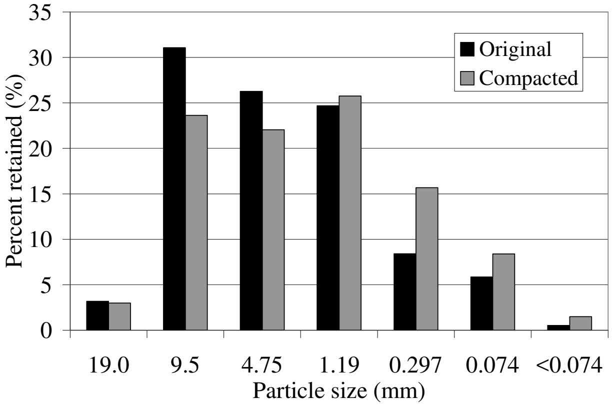

Fig. 4 Quantification of grain crushing

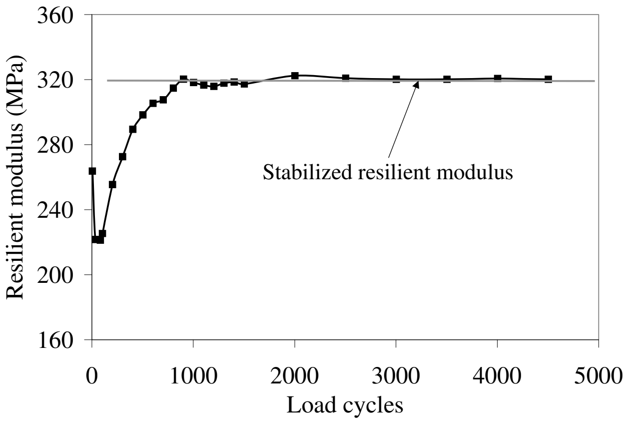

Fig. 5 Resilient modulus variation with loading cycles

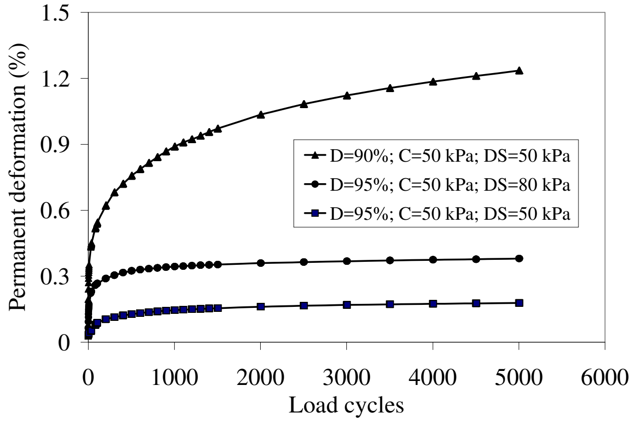

Fig. 6 Permanent deformation of the original material (D: density; C: confining pressure; DS: deviator stress)

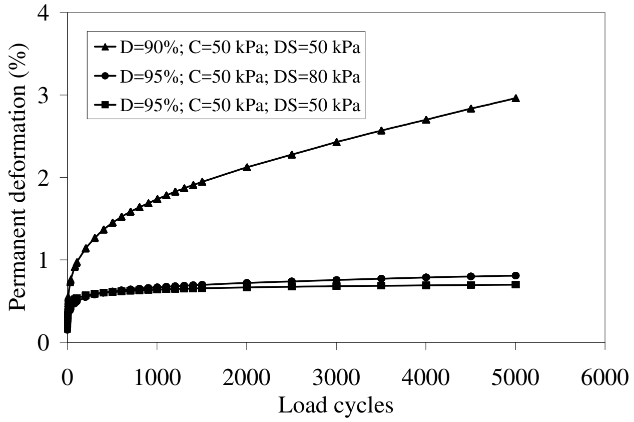

Fig. 7 Permanent deformation of the crushed material
(D: density; C: confining pressure; DS: deviator stress)

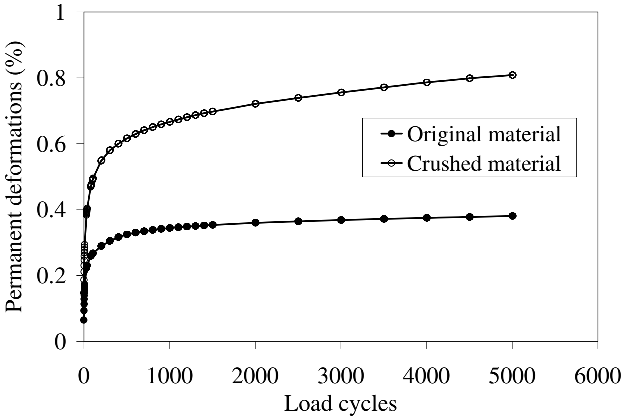

Fig. 8 Comparison of permanent deformation behaviours at a density of 95% of maximum modified Proctor density and a deviator stress of 80 kPa

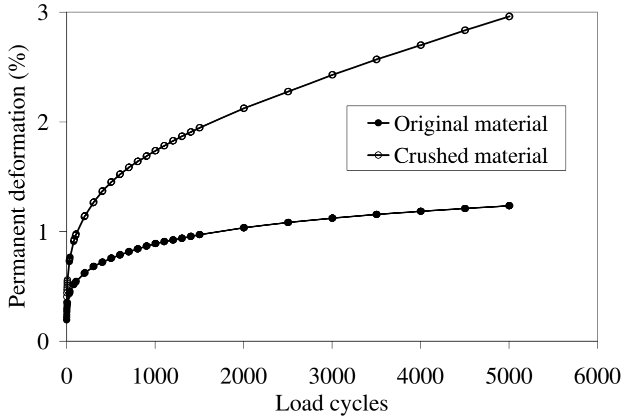

Fig. 9 Comparison of permanent deformation behaviours at a density of 90% of maximum modified Proctor density and a deviator stress of 50 kPa

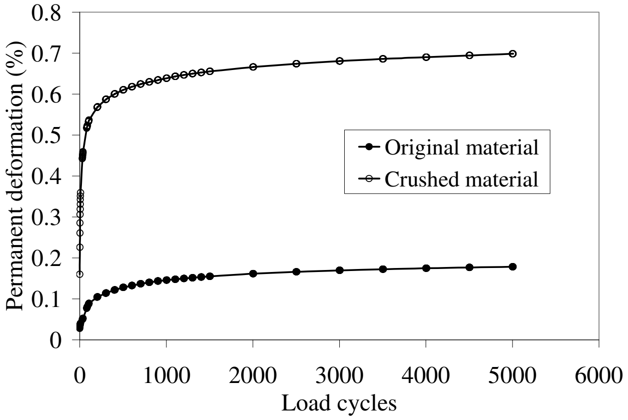

Fig. 10 Comparison of permanent deformation behaviours at a density of 95% of maximum modified Proctor density and a deviator stress of 50 kPa

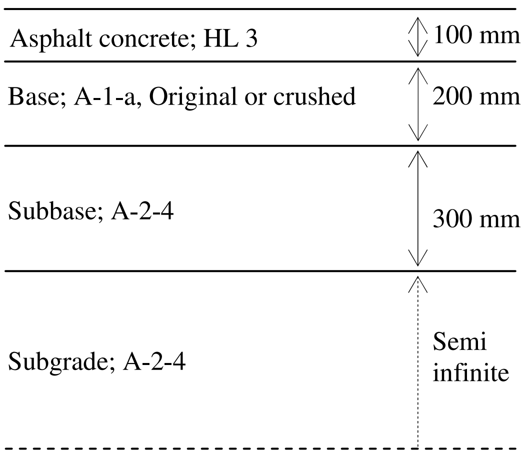

Fig. 11 Road structures analyzed

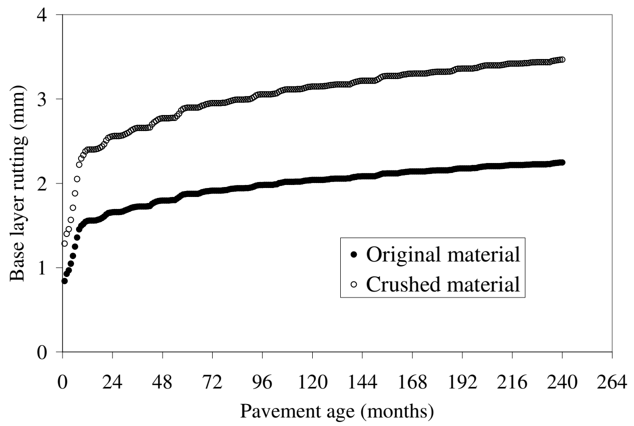

Fig. 12 Impact of grain crushing on rutting of the base layer

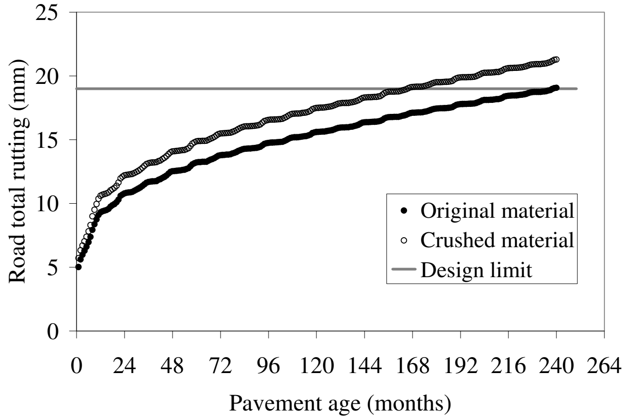

Fig. 13 Impact of grain crushing on total rutting of the road

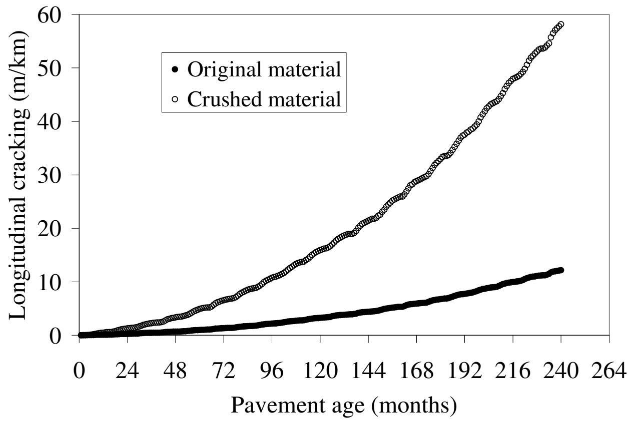

Fig. 14 Impact of grain crushing on longitudinal cracking

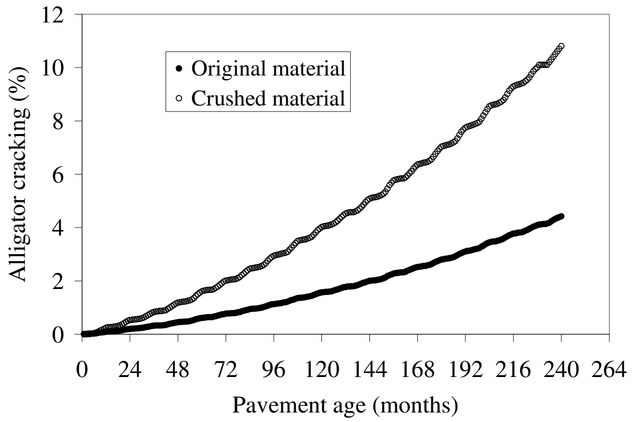

Fig. 15 Impact of grain crushing on alligator cracking