Recycled plastic granules and demolition wastes as construction materials: resilient moduli and strength characteristics

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1   **Recycled plastic granules and demolition wastes as construction materials:**

2   **resilient moduli and strength characteristics**

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47   **Abstract**

48   Vast quantities of plastic and demolition wastes are generated annually by municipal and

49   commercial industries in all developed and developing countries. The sustainable usage of

50   recycled plastic and demolition wastes as alternative construction materials has numerous

51   environmental and economic advantages. New opportunities to recycle plastic and demolition

52   wastes into alternative resource materials for construction industries, would mitigate landfill

53   issues and significantly reduce global carbon emissions. Infrastructure projects typically

54   consume significant quantities of virgin quarry materials, hence the usage of plastic and

55   demolition wastes as alternative construction materials will divert significant quantities of

56   these wastes from landfills. In this research, three types of recycled plastic waste granules:

57   Linear Low Density Polyethylene filled with Calcium Carbonate (LDCAL), High Density

58   Polyethylene (HDPE) and Low Density Polyethylene (LDPE) were evaluated in blends with

59   Crushed Brick (CB) and Reclaimed Asphalt Pavement (RAP). The blends prepared were

60   evaluated in terms of strength, stiffness and resilient moduli. Resilient moduli prediction

61   models were proposed using Repeated Load Triaxial (RLT) tests to characterize the stiffness

62   properties of the plastic/demolition waste blends. Polyethylene plastic granules with up to 5%

63   content were found to be suitable as a road construction material, when blended in

64   supplementary amounts with demolition wastes. This research is significant, as the usage of

65   plastics as a construction material, in combination with demolition wastes will expedite the

66   adoption of recycled by-products by construction industries.

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68   **Keywords:** plastic; demolition; waste; recycling; stiffness; strength

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Introduction

The production and landfilling of solid wastes has exacerbated carbon emissions and increased pollution in metropolitan cities worldwide. Management of wastes remains a global challenge for developed and developing countries alike [1]. The traditional approach of landfilling solid wastes is unsustainable and has become increasingly uneconomical, given the scarcity of land in urban precincts. Opportunities to recycle solid wastes into alternative resource materials are increasingly being sought by construction industries. The successful use of recycled wastes as a valuable resource material would significantly reduce the carbon footprint of road construction industries and furthermore reduce the demand for virgin quarry materials.

Plastic wastes comprise 8 to 12% of the municipal waste stream with approximately 190 million tonnes generated annually [2]. In Australia alone, 2.24 million tonnes of plastic waste were generated in 2008, which comprised 16% of the municipal waste stream [3]. Factors such as population growth, low production cost, and the wide variety of applications has led to an increasing production of plastics [4], with polyethylene products primarily contributing to the large volumes of plastic wastes [2].

Three types of polyethylene granules generated by the plastic recycling industries are Linear Low Density Polyethylene filled with Calcium Carbonate (LDCAL), High Density Polyethylene (HDPE) and Low Density Polyethylene (LDPE). Mineral fillers, such as calcium carbonate are added to polymers to enhance properties, as well as to reduce production costs. The mechanical properties of LDCAL, HDPE and LDPE such as density, maximum using temperature and tensile strength have been reported previously by several researchers [4-6]. Research on application of HDPE as a construction material has been limited to the usage of this material as a reinforcement in the form of fibers or strips. Benson

95   and Khire [7] researched on the usage of HDPE as a reinforcement material for sand and

96   reported that improvement in terms of bearing capacity, stiffness, resilient and shear

97   properties of the sand through geotechnical tests. Choudhari et al. [8] and Choudhari et al. [9]

98   reported that improvement in geotechnical properties of pavement base, subbase and

99   subgrade layers could be attained by using HDPE in the form of strips. Improvement of

100   flexible pavement material in terms of bearing capacity by introducing HDPE strips was also

101   reported by Jha et al. [10].

102   LDPE has been used in hot mix asphalt [11] and concrete [12, 13]. HDPE and LDPE granules

103   have been researched in combination with recycled concrete aggregates in pavement bases by

104   Yaghoubi et al. [14], who reported that despite slightly degradation in properties, the blends

105   were comparable to conventional quarry materials. Application of LDCAL as a civil

106   engineering construction material has been limited to reinforcing purposes, commonly in

107   form of geosynthetics [15, 16]. Lack of understanding of the properties of recycled plastic

108   wastes continues to limit their usage as a civil engineering construction material.

109   Crushed Brick (CB) and Reclaimed Asphalt Pavement (RCA) are generated by recycling the

110   waste solids after demolition activities. CB is obtained from demolition of masonry buildings,

111   while RAP is produced from the stockpiles of spent asphalt that has been removed from aged

112   roads [17]. The mechanical properties of CB and RAP have been found to be comparable to

113   conventional quarry materials in various civil engineering construction applications [18-24].

114   The aim of this research was to evaluate the viability of using waste plastic granules in

115   combination with demolition wastes as a road construction material. The plastic granules and

116   demolition wastes used in this research are by-products of recycling industries. The stiffness

117   and strength of the blends of plastic granules/demolition wastes were evaluated in this

118   research and resilient moduli models proposed to characterize the recycled blends. The

119   evaluation of plastic granules (LDCAL, HDPE or LDPE) in blends with demolition wastes

120   (CB, RAP) will enable further understanding of the strength, stiffness and performance of

121   these recycled by-products as a construction material. The optimum limits of the

122   supplementary plastics content that can be used in combination with demolition wastes would

123   bring new knowledge to civil engineering construction industries and expedite the adoption

124   of recycled by-products.

125   **Materials and Methods**

126   The materials used in this research were comprised of LDCAL, HDPE and LDPE plastic

127   granules together with CB and RAP demolition wastes from the state of Victoria, Australia.

128   The blends of plastics and demolition wastes used in this research are presented in **Table 1**.

129   Plastic contents of 3% and 5% were selected based on past work on plastics with recycled

130   concrete aggregates [14].

131   Gradation of the blends was investigated using Talbot and Richart [25] equation (aka Fuller's

132   equation) as presented in **Equation 1**, whereby PSD curves of the blends were fitted into the

133   equation to obtain the n exponent of each blend.

134   $P = 100 \times (\frac{d_i}{D_{max}})^n$ Equation 1

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136   where d_i is the size of the sieve in question, P is the total percent finer than the sieve in

137   question, D_{max} is the maximum particle size, and n is the exponent of the Fuller's Equation.

138   For a determined D_{max}, and diameters of d_i, the n exponent is the only variable parameter that

139   changes the gradation curve. Originally, Fuller and Thompson [26] reported a value of 0.5 for

140   the n exponent in order to achieve the highest density. However, later research works showed

141   that the n exponent of 0.5 might not be a fixed value for a gradation with the least voids. For

142   instance, in the 1960s Federal Highway Administration (FHWA), introduced an n exponent

143   of 0.45 for a PSD leading to the highest density [27].

144   Optimum Moisture Content (OMC) and Maximum Dry Density (MDD) of blends were

145   determined using modified Proctor method according to ASTM-D1557 [28]. A 152.4 mm

146   diameter mold with a height of 116.43 mm was used and samples were compacted in five

147   layers with 56 blows of the hammer on each layer. OMC and MDD were then obtained using

148   the compaction curves plotted based on the test results. For a uniform distribution of plastic

149   particles, the blends were mixed for several minutes. Also, for ensuring uniformity, a random

150   sample consisting of 95% CB and 5% plastic was divided into four quarters using a riffle and

151   the plastic content of each quarter was visually estimated. Segregation of aggregates was

152   avoided, by keeping the scoop as close as possible to the bottom of the mold when placing

153   the material.

154   California Bearing Ratio (CBR) was undertaken following ASTM-D1883 [29]. Samples were

155   compacted in five layers, each under modified Proctor compaction effort using 56 blows in a

156   152.4 mm diameter mold. Care was taken to control the uniform distribution of plastics in the

157   blends, as well as avoiding segregation while preparing and compacting the CBR samples.

158   Resilient properties of the blends due to the addition of supplementary amounts of LDCAL,

159   HDPE and LDPE plastic granules were evaluated using specialized Repeated Load Triaxial

160   (RLT) tests, and compared with typical values of resilient modulus for control (0% plastics)

161   CB and RAP. RLT tests simulate the repeated loads on civil engineering infrastructures when

162   subjected to traffic loads [30]. A triaxial cell was used with the universal testing machine to

163   carry out the RLT tests. RLT samples were prepared using a split compaction mold, 100 mm

164   in diameter and 202 mm in height. Samples were prepared in 8 layers, each layer under

165   modified Proctor compaction energy as described in ASTM-D1557 [28]. In the RLT testing,

166 a loading regime comprising of a haversine-shaped loading pulse with 0.1 s loading period

167 and 0.9 s resting period was used in accordance with AASHTO-T307-99 [30].

168 In RLT testing, changes of both confining stress and axial stress influence the resilient

169 modulus of the sample. As a result, in each RLT test, 15 different loading scenarios were

170 applied to cover different loading conditions. In this research, 180 data sets were obtained

171 from RLT testing on the 12 blends. The data sets were divided into 4 categories, as below, in

172 order to investigate the effect of type of plastic and plastic content on the model parameters.

173 • CB blends with 3% plastic content (45 data sets)

174 • CB blends with 5% plastic content (45 data sets)

175 • RAP blends with 3% plastic content (45 data sets)

176 • RAP blends with 5% plastic content (45 data sets)

177 The data sets were then evaluated using two three-parameter resilient modulus prediction

178 models, being Pappala et al. model [31] (aka octahedral stress state model) presented in

179 Equation 2 and AASHTO [32] model (aka modified universal model) presented in Equation

180 3. These models were developed for prediction and evaluation of the M_r values of granular

181 material applications:

182 $$M_r = p_a[k_1(\frac{\sigma_3}{p_a})^{k_2}(\frac{\sigma_d}{p_a})^{k_3}] \qquad\qquad \text{Equation 2}$$

183 $$M_r = k_1 p_a \left(\frac{\sigma_b}{p_a}\right)^{k_2} (\frac{\tau_{oct}}{p_a} + 1)^{k_3} \qquad\qquad \text{Equation 3}$$

184 In these equations, σ_3, σ_d and σ_b are confining, deviator and bulk stresses, respectively, p_a is

185 atmospheric pressure, τ_{oct} is octahedral shear stress. k_1, k_2 and k_3 are model parameters.

186 Stiffness characteristics of the blends, including UCS peak value, Young's modulus (E) and

187 secant modulus (E_{50}) were obtained by conducting Unconfined Compressive Strength (UCS).

188   In the plot obtained from the UCS test results, E is the slope of the stress versus strain curve

189   where the strains are recoverable. On this curve, E_{50} is the slope of the line connecting the

190   origin to the stress equal to the half of the UCS peak value. UCS tests were undertaken

191   following the completion of the non-destructive RLT tests on the same samples.

192   **Results and Discussion**

193   **Figure 1** presents the particle size distribution of the plastic and demolition wastes and also

194   shows images of the three plastic granules. The properties of the plastic wastes and

195   demolition wastes, including specific gravity (G_s), maximum particle size (D_{max}), mean

196   particle size (D_{50}), coefficient of uniformity (C_u) and coefficient of curvature (C_c) are

197   presented in **Table 2**. In accordance with the USCS classification system, the plastic granules

198   are found to be uniformly graded while the demolition wastes are classified as well graded

199   gravel-like materials. In terms of particle shape, as presented in **Table 2** sphericity of

200   LDCAL particles was the greatest (0.87). This value is close to that of an ideal cylinder with

201   sharp edges (0.874). Sphericity of HDPE and LDPE is lower and leans towards a half sphere

202   (0.84) and ideal cone (0.794), respectively. These have one sharp edge, whereas an ideal

203   cylinder has two edges.

204   **Figure 2** compares the *n* exponents obtained from gradation curves of control CB, control

205   RAP and the other blends. Evidently, introducing 3 and 5% contents of plastic granules to CB

206   and RAP did not cause significant changes in the PSD of the blends. In this figure, the range

207   of *n* exponent for the type C gradation of ASTM-D1241 [33] is also presented for comparison

208   purposes. The gradation properties of the plastic granules/demolition wastes are found to be

209   suitable for road construction materials, hence ensures high performance, strength and

210   bearing capacity. **Figure 2** shows that the CB blends are within the range required for a road

211   construction material; however, the RAP blends marginally exceed the recommended range.

212   **Table 3** presents the results of compaction and bearing capacity (CBR) tests on the plastic

213   granules/demolition waste blends. These tests were also conducted on control CB and RAP as

214   a reference bench-mark for evaluating the effect of adding plastic granules to these

215   demolition wastes. The plastics/RAP blends show a lower bearing capacity compared to

216   plastics/CB blends. This can be attributed to the plastics/CB blends having a more qualified

217   PSD that falls within the recommended range of gradation by ASTM-D1241 [33]. Adding

218   plastic granules to CB and RAP results in a lower MDD due to the lower specific gravity of

219   the plastic granules. Results also show that introducing plastic granules to CB and RAP

220   results in the reduction of bearing capacity of the control materials. This can be attributed to

221   the fact that plastic granules that replace the CB/RAP particles result in a softer surface,

222   leading to less internal friction and hence, lower bearing capacity.

223   Using the data obtained from UCS tests, the stress-strain curves of the plastic

224   granules/demolition wastes are presented in **Figure 3**. Generally, plastics/CB blends have

225   greater UCS values compared with their corresponding plastics/RAP blends, as was expected

226   due to the less qualified PSD of RAP blends. **Figure 3** also shows that the LDCAL and

227   LDPE granules result in samples with high and low UCS peak values, respectively. This can

228   be due to reduction of sphericity of particles from LDCAL to HDPE to LDPE.

229   Young's Modulus (E) and secant modulus at half of the UCS value (E_{50}) are two of the input

230   parameters for defining soil stiffness. Values of E and E_{50} were obtained from the stress-

231   strain curve of **Figure 3**. To investigate whether the samples are identical, in terms of void

232   ratio (e), values of e for each sample were calculated using soil model phase relationships.

233   **Table 4** presents values of E, and E_{50}, for the blends. In both CB and RAP blends, adding

234   LDCAL results in the highest and adding LDPE results in the lowest values of E. This means

235   that under the same load, blends with LDCAL have the least amount of deformation

236   compared with the other two types of plastics. Similar trend is observed in E_{50} of demolition

237   wastes/plastic blends. Also, increasing the plastic content in all blends results in lower E and

238   E_{50} values. This can be due to replacing more relatively rough surfaced particles of CB and

239   RAP with smooth surfaced particles of plastic.

240   **Figure 4** compares the UCS peak values of all blends of this research with typical range of

241   UCS values for control CB and RAP [17, 34-36]. The results show that an increase in the

242   plastic content of the sample results in a reduction of UCS values. Similar to the CBR

243   outcomes, this can be due to less surface roughness of the plastic particles, compared with

244   CB and RAP particles. High surface roughness of particles is known to result in high stiffness

245   of the blends [37].

246   **Figure 5** shows the RLT test results in form of the average of resilient moduli obtained from

247   15 sequences of the test for CB and RAP blends. This figure also shows the recommended

248   range of M_r values for base and subbase layers [38]. Resilient moduli of both plastic

249   granules/CB and plastics/RAP fall between the recommended ranges for M_r. Test results

250   show that in both the plastics/CB and plastics/RAP blends, increasing the plastic content

251   causes a subsequent reduction in M_r values. Replacing demolition wastes with smooth-

252   surfaced plastic granules is found to reduce the resilient modulus of the plastics/demolition

253   wastes. The higher surface roughness of the particles of a compacted sample tends to result in

254   a higher resilient modulus [39, 40].

255   Blends of LDCAL with CB and RAP have higher M_r values compared with corresponding

256   blends of HDPE and LDPE with CB and RAP. The same trend was previously observed with

257   regards to the Young's moduli (E) presented in **Table 4.** Resilient modulus is the ratio of

258   axial stress over recoverable strain, and E is the slope of the stress-strain curve where strains

259   are recoverable. Accordingly, the higher E values results in the higher M_r values, since under

260   the same stress, a plastic blend with high E has a lower recoverable strain. Other causes for

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261   high M_r values of plastic blends with LDCAL compared with blends with HDPE and LDPE

262   could be the particle shape and particle roughness. Scanning Electron Micrograph (SEM) of

263   these particles (**Figures 6a, 6b, and 6c**) shows that there is no significant difference in the

264   surface roughness of these particles. These SEM images have magnified the particles'

265   surfaces by 2000 times. Therefore, difference in surface roughness cannot be conclusively

266   attributed to greater M_r values of plastic blends with LDCAL. The resilient properties of

267   blends of granular materials are reduced when the blend consists of particles with low

268   sphericity [41], which is the case for the plastics/demolition wastes. **Figure 6** also shows the

269   surface of CB (**6d**) and RAP (**6e**) through SEM images that are 8000 times magnified. While

270   CB particles have both rough and smooth surface zones, in RAP particles the surface is

271   mostly smooth. This could also be the reason reported earlier for the higher stiffness of

272   plastics/CB compared with plastics/RAP blends.

273   **Figure 7** shows the resilient modulus versus maximum axial stress graphs for both

274   plastics/CB and plastics/RAP blends, under two different confinement pressures for each

275   blend. Evidently, high confinement pressures result in a high resilient modulus. This is due to

276   the increased particle interlock under high confining stresses as explained through predictive

277   resilient modulus models by Nguyen and Mohajerani [42]. Greater interlocking of aggregates

278   results in lower strains and therefore, lower M_r values. Trends in **Figure 7** also indicate that

279   when the confining stress is the same, at greater axial stresses, high M_r values are obtained as

280   a result of greater stress hardening [43].

281   **Figures 8 and 9** show the predicted versus measured M_r values along a 1:1 line. These

282   figures also present the model parameters calculated by conducting regression analysis of the

283   45 data sets for each category. For evaluation of the goodness of fit of test data in the models,

284   three statistical measurements were used, being S_e/S_y (standard accuracy), R^2 (coefficient of

285   determination), and RMSD (Root Mean Square Deviation). In the standard accuracy, S_y is the

286   standard deviation and S_e is standard error of estimate [44, 45]. Based on Witczak, Kaloush

287   [44] criterion, S_e/S_y inclining from 1 to 0 and R^2 inclining from 0 to 100 indicate better

288   accuracy of fit. Also, RMSD as proposed by Azam et al. [45] shows a better fit when it leans

289   towards 0% from 100%. S_e/S_y, R^2 and RMSD presented in **Figures 8 and 9** show an

290   "Excellent" fit for all blend with plastic content of 3% and "Good" fit for blends with plastic

291   content of 5%. Therefore, resilient behavior of these blends can be predicted using these well-

292   known models; however, as more plastic particles are introduced in the blends, accuracy of

293   these models is degraded.

294   According to the (Puppala et al. [31] model), k_2 and k_3 are positive, since as shown in **Figure**

295   **7**, M_r value is increased by increasing σ_3 and/or σ_d and k_3 being positive shows that resilient

296   modulus cannot be a negative value. Similarly, according to the (AASHTO [32] model), k_1

297   and k_2 model parameters are positive due to the similar reasons. However, the model

298   parameter k_3 which is an exponent for the octahedral shear stress is negative. It shows that as

299   the octahedral shear stress increases the M_r value decreases. High shear stress softens the

300   sample and results in greater deformations under the same load, and accordingly lower

301   resilient modulus. **Figures 8** and **9** show a reduction of k_2 (exponent corresponding to σ_d) and

302   k_3 (exponent corresponding to σ_3) according to the Puppala et al. [31] model by increasing

303   the plastic content in CB blends, but an increase in these parameters in RAP blends.

304   Similarly, in the AASHTO [32] model, the model parameter that represents the effect of σ_b

305   (k_2) is reduced by increasing the plastic content in CB blends and increased in RAP blends.

306   This shows that by increasing the plastic content, sensitivity of the models to bulk stress,

307   confining stress, and deviator stress is decreased in CB blends, but increased in RAP blends.

308   In addition, the true value of k_3, regardless of its sign, is greater for plastics/CB blends with

309   3% plastic content but lower in plastics/RAP blends with 3% plastic content. This shows that

310 with respect to octahedral shear stress the models get more sensitive in CB blends and less

311 sensitive in RAP blends as more plastic particles are introduced in the mixture.

312 **Conclusions**

313 In this research, three types of recycled plastic granules (LDPE, HDPE, and LDCAL) and

314 two types of demolition wastes (CB and RAP) were blended to evaluate their usage as a road

315 construction material. These plastics/demolition wastes were then evaluated in terms of

316 stiffness and resilient characteristics. The following results are obtained from the outcomes of

317 this research:

318   1- Adding 3-5% of plastic granules did not cause a noticeable change in the PSD of the
319   pure CB and RAP.
320   2- Among the plastics/demolition waste blends, LDCAL show high bearing capacity.
321   Generally, even though adding 3% and 5% plastic granules to the demolition wastes
322   degrades their bearing capacity, the bearing capacity (CBR) of the blends shows that
323   the plastics/demolition wastes blends are suitable in a range of civil engineering
324   applications, such as bases, subbases, subgrades and embankment fills.
325   3- Results of UCS tests show that, among the corresponding plastic blends, those with
326   LDCAL granules have the greatest stiffness and higher Young's modulus than those
327   with LDPE granules. Also, in general, introducing more plastic granules lower the
328   stiffness characteristics of the blends.
329   4- In terms of resilient behavior, samples prepared from blends with LDCAL granules
330   result in the highest resilient modulus. RLT test results show that M_r values of all
331   plastic blends fall within the range recommended for high quality construction
332   materials, such as base and subbase. In addition, adding 3-5% plastic granules to CB
333   and RAP would result in sufficient resilient moduli for road construction applications.

334   5- SEM images indicate insignificant difference in surface roughness of all three plastic

335   granules. Therefore, differences in CBR, UCS and M_r values of the corresponding

336   blends with the same plastic content could be due to difference in sphericity of the

337   particles.

338   6- The bearing capacity, stiffness and resilient modulus of plastics/CB and plastics/RAP

339   are reduced by adding a larger content of plastic granules. This is due to introducing

340   smooth-surfaced particles (LDCAL, HDPE, LDPE) to replace the particles with high

341   surface roughness (CB and RAP).

342   7- In spite of this, plastic blends with CB/RAP indicate sufficient engineering

343   characteristics as civil engineering construction material. The optimum limits of the

344   supplementary plastics content that can be used in combination with demolition

345   wastes would bring new knowledge to civil engineering construction industries and

346   expedite the adoption of recycled by-products.

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495   **LIST OF TABLES**

496   **Table 1**. Blends of plastic granules/demolition wastes used in this research

497   **Table 2**. Physical properties of plastic granules and demolition wastes.

498   **Table 3**. Results of compaction and CBR tests on the plastic blends

499   **Table 4**. Young's modulus and secant modulus of the plastic blends

500

501

502   Table 1. Blends of demolition wastes/plastic granules used in this research

Blend Composition	Blend Name
Control CB	CB
3%LDCAL + 97%CB	LDCAL3/CB97
3%HDPE + 97% CB	HDPE3/CB97
3%LDPE + 97%CB	LDPE3/CB97
5%LDCAL + 95%CB	LDCAL5/CB95
5%HDPE + 95%CB	HDPE5/CB95
5%LDPE + 95%CB	LDPE5/CB95
Control RAP	RAP
3%LDCAL + 97%RAP	LDCAL3/RAP97
3%HDPE + 97%RAP	HDPE3/RAP97
3%LDPE + 97%RAP	LDPE3/RAP97
5%LDCAL + 95%RAP	LDCAL5/RAP95
5%HDPE + 95%RAP	HDPE5/RAP95
5%LDPE + 95%RAP	LDPE5/RAP95

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517   Table 2. Physical properties of CB, RAP, LDCAL, HDPE and LDPE

Material	G_s	D_{max}	D_{50}	C_u	C_c	USCS Classification	Particle Sphericity
CB	2.64	19.00	4.50	21.4	1.1	Well Graded Gravel	-
RAP	2.52	19.00	4.80	14.6	1.7	Well Graded Gravel	-
LDCAL	1.28	4.75	2.80	1.5	0.9	Uniformly Graded	0.870
HDPE	0.94	4.75	3.51	2.0	1.0	Uniformly Graded	0.862
LDPE	0.92	6.30	4.04	1.7	0.9	Uniformly Graded	0.793

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521   Table 3. Results of compaction and CBR tests on the blends

Blend	MDD (Mg/m^3)	OMC (%)	CBR (%)
CB	1.985	11.3	114-130
LDCAL3/CB97	1.919	11.8	93-109
HDPE3/CB97	1.889	11.6	95-106
LDPE3/CB97	1.878	11.5	91-103
LDCAL5/CB95	1.821	11.6	81-89
HDPE5/CB95	1.793	11.5	80-86
LDPE5/CB95	1.790	11.3	71-79
RAP	2.001	10.8	20-26
LDCAL3/RAP97	1.965	10.0	14-19
HDPE3/RAP97	1.926	9.9	14-17
LDPE3/RAP97	1.919	9.7	11-15
LDCAL5/RAP95	1.951	9.7	13-17
HDPE5/RAP95	1.889	9.5	14-16
LDPE5/RAP95	1.874	9.2	11-14

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526   Table 4. Young's modulus and secant modulus of the blends

Blend	E (MPa)	E_{50} (MPa)
LDCAL3/CB97	25.0	23.9
HDPE3/CB97	20.0	19.7
LDPE3/CB97	16.7	15.6
LDCAL5/CB95	12.5	12.0
HDPE5/CB95	10.8	10.7
LDPE5/CB95	6.9	5.6
LDCAL3/RAP97	10.0	9.4
HDPE3/RAP97	8.3	8.3
LDPE3/RAP97	7.7	7.5
LDCAL5/RAP95	7.8	6.8
HDPE5/RAP95	6.9	6.9
LDPE5/RAP95	5.0	4.9

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a

- LDCAL3/CB97
- HDPE3/CB97
- LDPE3/CB97
- LDCAL5/CB95
- HDPE5/CB95
- LDPE5/CB95

Axial Stress (kPa)

Axial Strain (%)

b

- LDCAL3/RAP97
- HDPE3/RAP97
- LDCAL5/RAP95
- LDPE5/RAP95
- HDPE5/RAP95
- LDPE3/RAP97

Axial Stress (kPa)

Axial Strain (%)

a

LDCAL3/CB97
HDPE3/CB97
LDPE3/CB97

k_1	1552.5
k_2	0.432
k_3	0.320
n	45
S_e/S_y	0.25
R^2	0.94
RMSD (%)	9.4

b

LDCAL3/CB97
HDPE3/CB97
LDPE3/CB97

k_1	0.549
k_2	0.796
k_3	-0.101
n	45
S_e/S_y	0.29
R^2	0.92
RMSD (%)	10.9

c

LDCAL5/CB95
HDPE5/CB95
LDPE5/CB95

k_1	1365.0
k_2	0.531
k_3	0.204
n	45
S_e/S_y	0.35
R^2	0.88
RMSD (%)	18.1

d

LDCAL5/CB95
HDPE5/CB95
LDPE5/CB95

k_1	0.479
k_2	0.755
k_3	-0.039
n	45
S_e/S_y	0.36
R^2	0.88
RMSD (%)	18.2

Predicted M_r (MPa)

Measured M_r (Mpa)

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Predicted M_r (MPa) vs Measured M_r (Mpa)

- △ LDCAL3/RAP97
- ✕ HDPE3/RAP97
- ◇ LDPE3/RAP97

k_1	2548.0
k_2	0.506
k_3	0.157
n	45
S_e/S_y	0.26
R^2	0.94
RMSD (%)	10.0

b

Predicted M_r (MPa) vs Measured M_r (Mpa)

- △ LDCAL3/RAP97
- ✕ HDPE3/RAP97
- ◇ LDPE3/RAP97

k_1	0.993
k_2	0.734
k_3	-0.208
n	45
S_e/S_y	0.26
R^2	0.94
RMSD (%)	9.5

c

Predicted M_r (MPa) vs Measured M_r (Mpa)

- △ LDCAL5/RAP95
- ✕ HDPE5/RAP95
- ◇ LDPE5/RAP95

k_1	2017.0
k_2	0.512
k_3	0.212
n	45
S_e/S_y	0.44
R^2	0.81
RMSD (%)	19.4

d

Predicted M_r (MPa) vs Measured M_r (Mpa)

- △ LDCAL5/RAP95
- ✕ HDPE5/RAP95
- ◇ LDPE5/RAP95

k_1	0.722
k_2	0.751
k_3	-0.059
n	45
S_e/S_y	0.44
R^2	0.81
RMSD (%)	19.4