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

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Abstract

Vast quantities of plastic and demolition wastes are generated annually by municipal and commercial industries in all developed and developing countries. The sustainable usage of recycled plastic and demolition wastes as alternative construction materials has numerous environmental and economic advantages. New opportunities to recycle plastic and demolition wastes into alternative resource materials for construction industries, would mitigate landfill issues and significantly reduce global carbon emissions. Infrastructure projects typically consume significant quantities of virgin quarry materials, hence the usage of plastic and demolition wastes as alternative construction materials will divert significant quantities of these wastes from landfills. In this research, three types of recycled plastic waste granules: Linear Low Density Polyethylene filled with Calcium Carbonate (LDCAL), High Density Polyethylene (HDPE) and Low Density Polyethylene (LDPE) were evaluated in blends with Crushed Brick (CB) and Reclaimed Asphalt Pavement (RAP). The blends prepared were evaluated in terms of strength, stiffness and resilient moduli. Resilient moduli prediction models were proposed using Repeated Load Triaxial (RLT) tests to characterize the stiffness properties of the plastic/demolition waste blends. Polyethylene plastic granules with up to 5% content were found to be suitable as a road construction material, when blended in supplementary amounts with demolition wastes. This research is significant, as the usage of plastics as a construction material, in combination with demolition wastes will expedite the adoption of recycled by-products by construction industries.

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

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 and Khire [7] researched on the usage of HDPE as a reinforcement material for sand and reported that improvement in terms of bearing capacity, stiffness, resilient and shear properties of the sand through geotechnical tests. Choudhari et al. [8] and Choudhari et al. [9] reported that improvement in geotechnical properties of pavement base, subbase and subgrade layers could be attained by using HDPE in the form of strips. Improvement of flexible pavement material in terms of bearing capacity by introducing HDPE strips was also reported by Jha et al. [10].

LDPE has been used in hot mix asphalt [11] and concrete [12, 13]. HDPE and LDPE granules have been researched in combination with recycled concrete aggregates in pavement bases by Yaghoubi et al. [14], who reported that despite slightly degradation in properties, the blends were comparable to conventional quarry materials. Application of LDCAL as a civil engineering construction material has been limited to reinforcing purposes, commonly in form of geosynthetics [15, 16]. Lack of understanding of the properties of recycled plastic wastes continues to limit their usage as a civil engineering construction material.

Crushed Brick (CB) and Reclaimed Asphalt Pavement (RCA) are generated by recycling the waste solids after demolition activities. CB is obtained from demolition of masonry buildings, while RAP is produced from the stockpiles of spent asphalt that has been removed from aged roads [17]. The mechanical properties of CB and RAP have been found to be comparable to conventional quarry materials in various civil engineering construction applications [18-24].

The aim of this research was to evaluate the viability of using waste plastic granules in combination with demolition wastes as a road construction material. The plastic granules and demolition wastes used in this research are by-products of recycling industries. The stiffness and strength of the blends of plastic granules/demolition wastes were evaluated in this research and resilient moduli models proposed to characterize the recycled blends. The evaluation of plastic granules (LDCAL, HDPE or LDPE) in blends with demolition wastes (CB, RAP) will enable further understanding of the strength, stiffness and performance of these recycled by-products as a construction material. The optimum limits of the supplementary plastics content that can be used in combination with demolition wastes would bring new knowledge to civil engineering construction industries and expedite the adoption of recycled by-products.

Materials and Methods

The materials used in this research were comprised of LDCAL, HDPE and LDPE plastic granules together with CB and RAP demolition wastes from the state of Victoria, Australia. The blends of plastics and demolition wastes used in this research are presented in **Table 1**. Plastic contents of 3% and 5% were selected based on past work on plastics with recycled concrete aggregates [14].

Gradation of the blends was investigated using Talbot and Richart [25] equation (aka Fuller's equation) as presented in **Equation 1**, whereby PSD curves of the blends were fitted into the equation to obtain the n exponent of each blend.

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

where d_i is the size of the sieve in question, P is the total percent finer than the sieve in question, $D_{\max}$ is the maximum particle size, and n is the exponent of the Fuller's Equation.

For a determined $D_{\max}$, and diameters of d_i, the n exponent is the only variable parameter that changes the gradation curve. Originally, Fuller and Thompson [26] reported a value of 0.5 for the n exponent in order to achieve the highest density. However, later research works showed that the n exponent of 0.5 might not be a fixed value for a gradation with the least voids. For instance, in the 1960s Federal Highway Administration (FHWA), introduced an *n* exponent of 0.45 for a PSD leading to the highest density [27].

Optimum Moisture Content (OMC) and Maximum Dry Density (MDD) of blends were determined using modified Proctor method according to ASTM-D1557 [28]. A 152.4 mm diameter mold with a height of 116.43 mm was used and samples were compacted in five layers with 56 blows of the hammer on each layer. OMC and MDD were then obtained using the compaction curves plotted based on the test results. For a uniform distribution of plastic particles, the blends were mixed for several minutes. Also, for ensuring uniformity, a random sample consisting of 95% CB and 5% plastic was divided into four quarters using a riffle and the plastic content of each quarter was visually estimated. Segregation of aggregates was avoided, by keeping the scoop as close as possible to the bottom of the mold when placing the material.

California Bearing Ratio (CBR) was undertaken following ASTM-D1883 [29]. Samples were compacted in five layers, each under modified Proctor compaction effort using 56 blows in a 152.4 mm diameter mold. Care was taken to control the uniform distribution of plastics in the blends, as well as avoiding segregation while preparing and compacting the CBR samples.

Resilient properties of the blends due to the addition of supplementary amounts of LDCAL, HDPE and LDPE plastic granules were evaluated using specialized Repeated Load Triaxial (RLT) tests, and compared with typical values of resilient modulus for control (0% plastics) CB and RAP. RLT tests simulate the repeated loads on civil engineering infrastructures when subjected to traffic loads [30]. A triaxial cell was used with the universal testing machine to carry out the RLT tests. RLT samples were prepared using a split compaction mold, 100 mm in diameter and 202 mm in height. Samples were prepared in 8 layers, each layer under modified Proctor compaction energy as described in ASTM-D1557 [28]. In the RLT testing, a loading regime comprising of a haversine-shaped loading pulse with 0.1 s loading period and 0.9 s resting period was used in accordance with AASHTO-T307-99 [30].

In RLT testing, changes of both confining stress and axial stress influence the resilient modulus of the sample. As a result, in each RLT test, 15 different loading scenarios were applied to cover different loading conditions. In this research, 180 data sets were obtained from RLT testing on the 12 blends. The data sets were divided into 4 categories, as below, in order to investigate the effect of type of plastic and plastic content on the model parameters.

- CB blends with 3% plastic content (45 data sets)
- CB blends with 5% plastic content (45 data sets)
- RAP blends with 3% plastic content (45 data sets)
- RAP blends with 5% plastic content (45 data sets)

The data sets were then evaluated using two three-parameter resilient modulus prediction models, being Pappala et al. model [31] (aka octahedral stress state model) presented in Equation 2 and AASHTO [32] model (aka modified universal model) presented in Equation 3. These models were developed for prediction and evaluation of the M_r values of granular material applications:

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

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

In these equations, σ_3, σ_d and σ_b are confining, deviator and bulk stresses, respectively, p_a is atmospheric pressure, τ_{oct} is octahedral shear stress. k_1, k_2 and k_3 are model parameters.

Stiffness characteristics of the blends, including UCS peak value, Young's modulus (E) and secant modulus (E_{50}) were obtained by conducting Unconfined Compressive Strength (UCS).

In the plot obtained from the UCS test results, E is the slope of the stress versus strain curve where the strains are recoverable. On this curve, E_{50} is the slope of the line connecting the origin to the stress equal to the half of the UCS peak value. UCS tests were undertaken following the completion of the non-destructive RLT tests on the same samples.

Results and Discussion

Figure 1 presents the particle size distribution of the plastic and demolition wastes and also shows images of the three plastic granules. The properties of the plastic wastes and demolition wastes, including specific gravity (G_s), maximum particle size (D_{max}), mean particle size (D_{50}), coefficient of uniformity (C_u) and coefficient of curvature (C_c) are presented in **Table 2**. In accordance with the USCS classification system, the plastic granules are found to be uniformly graded while the demolition wastes are classified as well graded gravel-like materials. In terms of particle shape, as presented in **Table 2** sphericity of LDCAL particles was the greatest (0.87). This value is close to that of an ideal cylinder with sharp edges (0.874). Sphericity of HDPE and LDPE is lower and leans towards a half sphere (0.84) and ideal cone (0.794), respectively. These have one sharp edge, whereas an ideal cylinder has two edges.

Figure 2 compares the *n* exponents obtained from gradation curves of control CB, control RAP and the other blends. Evidently, introducing 3 and 5% contents of plastic granules to CB and RAP did not cause significant changes in the PSD of the blends. In this figure, the range of *n* exponent for the type C gradation of ASTM-D1241 [33] is also presented for comparison purposes. The gradation properties of the plastic granules/demolition wastes are found to be suitable for road construction materials, hence ensures high performance, strength and bearing capacity. **Figure 2** shows that the CB blends are within the range required for a road construction material; however, the RAP blends marginally exceed the recommended range.

Table 3 presents the results of compaction and bearing capacity (CBR) tests on the plastic granules/demolition waste blends. These tests were also conducted on control CB and RAP as a reference bench-mark for evaluating the effect of adding plastic granules to these demolition wastes. The plastics/RAP blends show a lower bearing capacity compared to plastics/CB blends. This can be attributed to the plastics/CB blends having a more qualified PSD that falls within the recommended range of gradation by ASTM-D1241 [33]. Adding plastic granules to CB and RAP results in a lower MDD due to the lower specific gravity of the plastic granules. Results also show that introducing plastic granules to CB and RAP results in the reduction of bearing capacity of the control materials. This can be attributed to the fact that plastic granules that replace the CB/RAP particles result in a softer surface, leading to less internal friction and hence, lower bearing capacity.

Using the data obtained from UCS tests, the stress-strain curves of the plastic granules/demolition wastes are presented in **Figure 3**. Generally, plastics/CB blends have greater UCS values compared with their corresponding plastics/RAP blends, as was expected due to the less qualified PSD of RAP blends. **Figure 3** also shows that the LDCAL and LDPE granules result in samples with high and low UCS peak values, respectively. This can be due to reduction of sphericity of particles from LDCAL to HDPE to LDPE.

Young's Modulus (E) and secant modulus at half of the UCS value (E_{50}) are two of the input parameters for defining soil stiffness. Values of E and E_{50} were obtained from the stress-strain curve of **Figure 3**. To investigate whether the samples are identical, in terms of void ratio (e), values of e for each sample were calculated using soil model phase relationships. **Table 4** presents values of E, and E_{50}, for the blends. In both CB and RAP blends, adding LDCAL results in the highest and adding LDPE results in the lowest values of E. This means that under the same load, blends with LDCAL have the least amount of deformation compared with the other two types of plastics. Similar trend is observed in E_{50} of demolition wastes/plastic blends. Also, increasing the plastic content in all blends results in lower E and E_{50} values. This can be due to replacing more relatively rough surfaced particles of CB and RAP with smooth surfaced particles of plastic.

Figure 4 compares the UCS peak values of all blends of this research with typical range of UCS values for control CB and RAP [17, 34-36]. The results show that an increase in the plastic content of the sample results in a reduction of UCS values. Similar to the CBR outcomes, this can be due to less surface roughness of the plastic particles, compared with CB and RAP particles. High surface roughness of particles is known to result in high stiffness of the blends [37].

Figure 5 shows the RLT test results in form of the average of resilient moduli obtained from 15 sequences of the test for CB and RAP blends. This figure also shows the recommended range of M_r values for base and subbase layers [38]. Resilient moduli of both plastic granules/CB and plastics/RAP fall between the recommended ranges for M_r. Test results show that in both the plastics/CB and plastics/RAP blends, increasing the plastic content causes a subsequent reduction in M_r values. Replacing demolition wastes with smooth-surfaced plastic granules is found to reduce the resilient modulus of the plastics/demolition wastes. The higher surface roughness of the particles of a compacted sample tends to result in a higher resilient modulus [39, 40].

Blends of LDCAL with CB and RAP have higher M_r values compared with corresponding blends of HDPE and LDPE with CB and RAP. The same trend was previously observed with regards to the Young's moduli (E) presented in **Table 4.** Resilient modulus is the ratio of axial stress over recoverable strain, and E is the slope of the stress-strain curve where strains are recoverable. Accordingly, the higher E values results in the higher M_r values, since under the same stress, a plastic blend with high E has a lower recoverable strain. Other causes for high M_r values of plastic blends with LDCAL compared with blends with HDPE and LDPE could be the particle shape and particle roughness. Scanning Electron Micrograph (SEM) of these particles (**Figures 6a, 6b, and 6c)** shows that there is no significant difference in the surface roughness of these particles. These SEM images have magnified the particles' surfaces by 2000 times. Therefore, difference in surface roughness cannot be conclusively attributed to greater M_r values of plastic blends with LDCAL. The resilient properties of blends of granular materials are reduced when the blend consists of particles with low sphericity [41], which is the case for the plastics/demolition wastes. **Figure 6** also shows the surface of CB (**6d**) and RAP (**6e**) through SEM images that are 8000 times magnified. While CB particles have both rough and smooth surface zones, in RAP particles the surface is mostly smooth. This could also be the reason reported earlier for the higher stiffness of plastics/CB compared with plastics/RAP blends.

Figure 7 shows the resilient modulus versus maximum axial stress graphs for both plastics/CB and plastics/RAP blends, under two different confinement pressures for each blend. Evidently, high confinement pressures result in a high resilient modulus. This is due to the increased particle interlock under high confining stresses as explained through predictive resilient modulus models by Nguyen and Mohajerani [42]. Greater interlocking of aggregates results in lower strains and therefore, lower M_r values. Trends in **Figure 7** also indicate that when the confining stress is the same, at greater axial stresses, high M_r values are obtained as a result of greater stress hardening [43].

Figures 8 and 9 show the predicted versus measured M_r values along a 1:1 line. These figures also present the model parameters calculated by conducting regression analysis of the 45 data sets for each category. For evaluation of the goodness of fit of test data in the models, three statistical measurements were used, being S_e/S_y (standard accuracy), R^2 (coefficient of determination), and RMSD (Root Mean Square Deviation). In the standard accuracy, S_y is the standard deviation and S_e is standard error of estimate [44, 45]. Based on Witczak, Kaloush [44] criterion, S_e/S_y inclining from 1 to 0 and R^2 inclining from 0 to 100 indicate better accuracy of fit. Also, RMSD as proposed by Azam et al. [45] shows a better fit when it leans towards 0% from 100%. S_e/S_y, R^2 and RMSD presented in **Figures 8 and 9** show an "Excellent" fit for all blend with plastic content of 3% and "Good" fit for blends with plastic content of 5%. Therefore, resilient behavior of these blends can be predicted using these well-known models; however, as more plastic particles are introduced in the blends, accuracy of these models is degraded.

According to the (Puppala et al. [31] model), k_2 and k_3 are positive, since as shown in **Figure 7**, M_r value is increased by increasing σ_3 and/or σ_d and k_3 being positive shows that resilient modulus cannot be a negative value. Similarly, according to the (AASHTO [32] model), k_1 and k_2 model parameters are positive due to the similar reasons. However, the model parameter k_3 which is an exponent for the octahedral shear stress is negative. It shows that as the octahedral shear stress increases the M_r value decreases. High shear stress softens the sample and results in greater deformations under the same load, and accordingly lower resilient modulus. **Figures 8** and **9** show a reduction of k_2 (exponent corresponding to σ_d) and k_3 (exponent corresponding to σ_3) according to the Puppala et al. [31] model by increasing the plastic content in CB blends, but an increase in these parameters in RAP blends. Similarly, in the AASHTO [32] model, the model parameter that represents the effect of σ_b (k_2) is reduced by increasing the plastic content in CB blends and increased in RAP blends. This shows that by increasing the plastic content, sensitivity of the models to bulk stress, confining stress, and deviator stress is decreased in CB blends, but increased in RAP blends. In addition, the true value of k_3, regardless of its sign, is greater for plastics/CB blends with 3% plastic content but lower in plastics/RAP blends with 3% plastic content. This shows that with respect to octahedral shear stress the models get more sensitive in CB blends and less sensitive in RAP blends as more plastic particles are introduced in the mixture.

Conclusions

In this research, three types of recycled plastic granules (LDPE, HDPE, and LDCAL) and two types of demolition wastes (CB and RAP) were blended to evaluate their usage as a road construction material. These plastics/demolition wastes were then evaluated in terms of stiffness and resilient characteristics. The following results are obtained from the outcomes of this research:

1- Adding 3-5% of plastic granules did not cause a noticeable change in the PSD of the pure CB and RAP.

2- Among the plastics/demolition waste blends, LDCAL show high bearing capacity. Generally, even though adding 3% and 5% plastic granules to the demolition wastes degrades their bearing capacity, the bearing capacity (CBR) of the blends shows that the plastics/demolition wastes blends are suitable in a range of civil engineering applications, such as bases, subbases, subgrades and embankment fills.

3- Results of UCS tests show that, among the corresponding plastic blends, those with LDCAL granules have the greatest stiffness and higher Young's modulus than those with LDPE granules. Also, in general, introducing more plastic granules lower the stiffness characteristics of the blends.

4- In terms of resilient behavior, samples prepared from blends with LDCAL granules result in the highest resilient modulus. RLT test results show that M_r values of all plastic blends fall within the range recommended for high quality construction materials, such as base and subbase. In addition, adding 3-5% plastic granules to CB and RAP would result in sufficient resilient moduli for road construction applications.

5- SEM images indicate insignificant difference in surface roughness of all three plastic granules. Therefore, differences in CBR, UCS and M_r values of the corresponding blends with the same plastic content could be due to difference in sphericity of the particles.

6- The bearing capacity, stiffness and resilient modulus of plastics/CB and plastics/RAP are reduced by adding a larger content of plastic granules. This is due to introducing smooth-surfaced particles (LDCAL, HDPE, LDPE) to replace the particles with high surface roughness (CB and RAP).

7- In spite of this, plastic blends with CB/RAP indicate sufficient engineering characteristics as civil engineering construction material. The optimum limits of the supplementary plastics content that can be used in combination with demolition wastes would bring new knowledge to civil engineering construction industries and expedite the adoption of recycled by-products.

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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

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

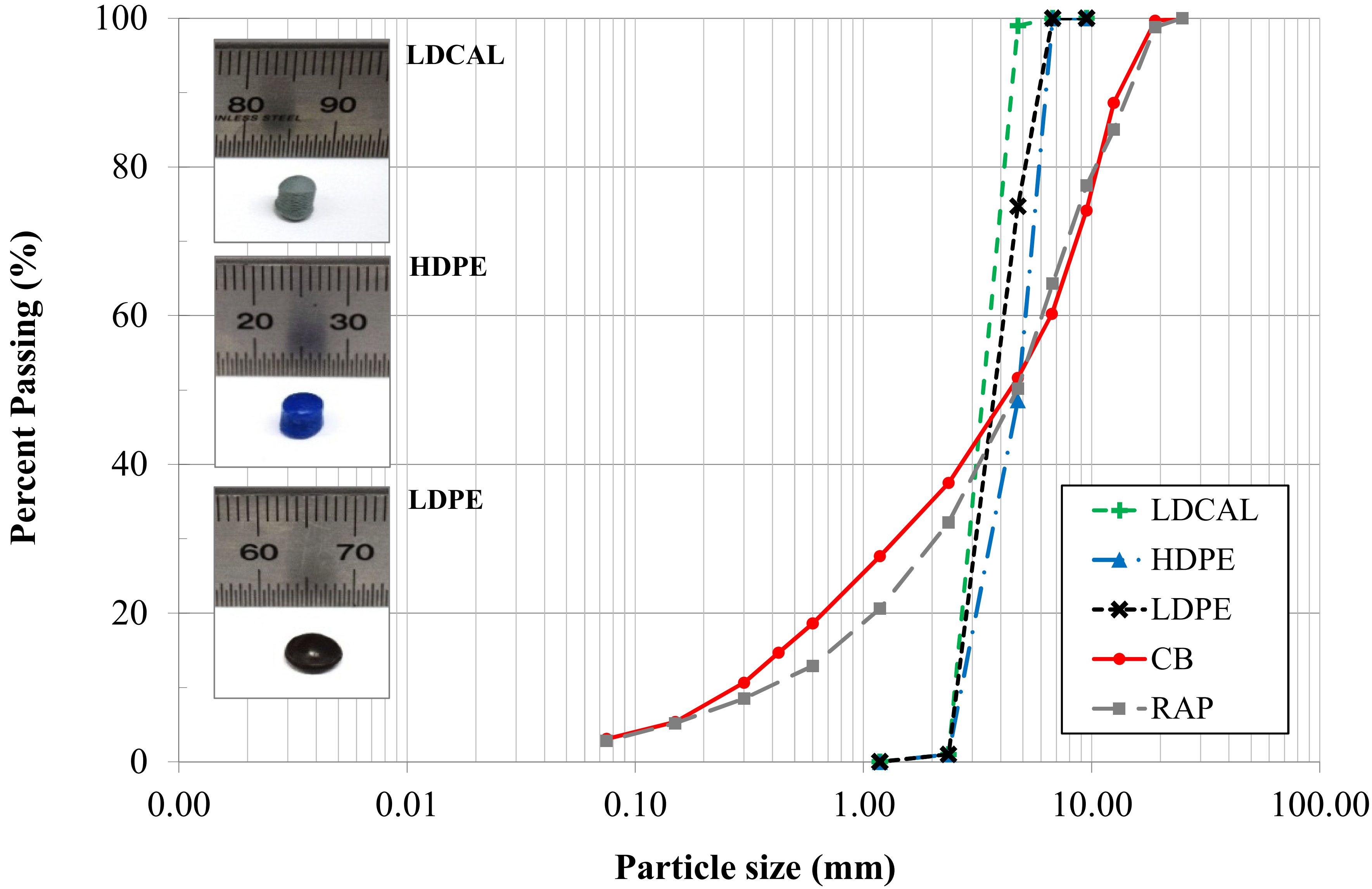
Material	G_s	D_{max}	D_{50}	C_u	C_c	USCS Classification	Particle Sphericity
CB	2.64	19.00	4.50	21.4	1.1	Well Graded Gravel	-
RAP	2.52	19.00	4.80	14.6	1.7	Well Graded Gravel	-
LDCAL	1.28	4.75	2.80	1.5	0.9	Uniformly Graded	0.870
HDPE	0.94	4.75	3.51	2.0	1.0	Uniformly Graded	0.862
LDPE	0.92	6.30	4.04	1.7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

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

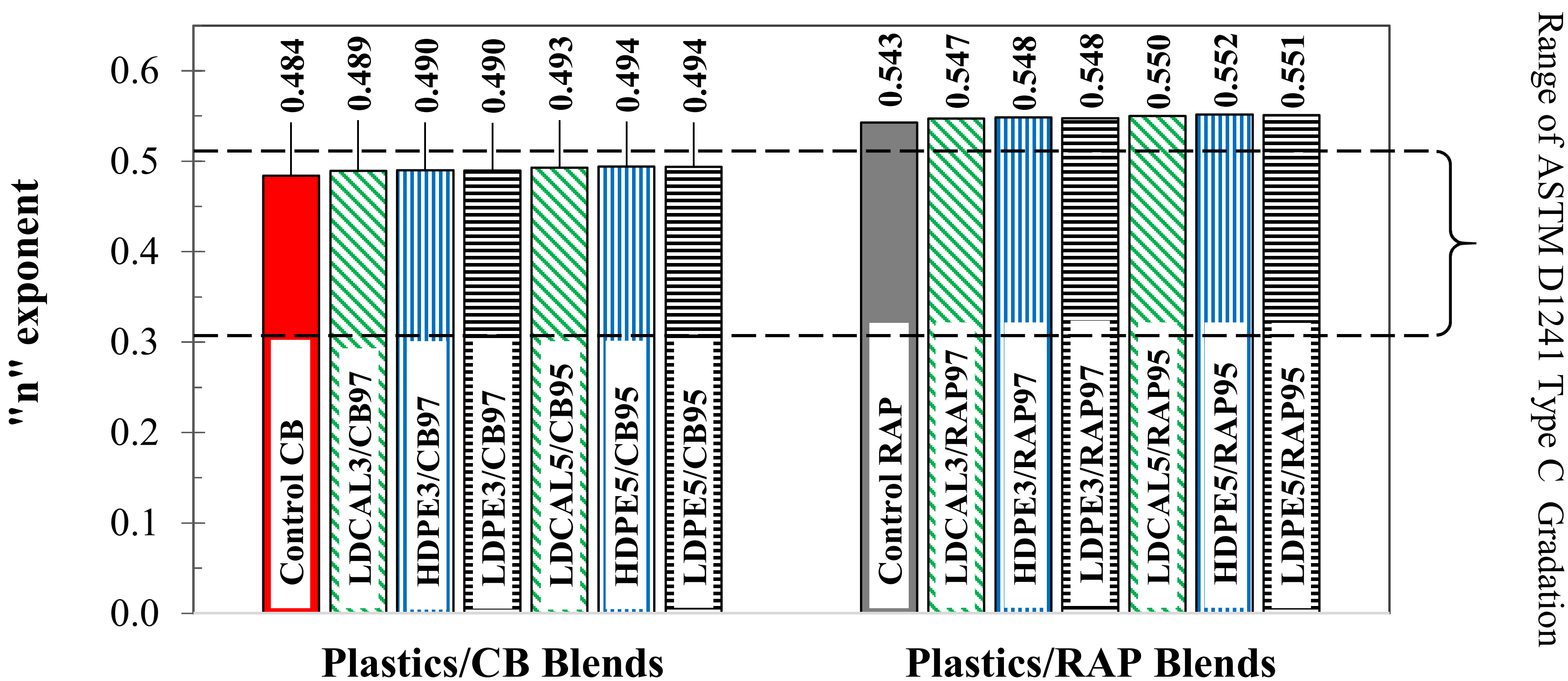
Blend	MDD (Mg/m^3)	OMC (%)	CBR (%)
CB	1.985	11.3	114-130
LDCAL3/CB97	1.919	11.8	93-109
HDPE3/CB97	1.889	11.6	95-106
LDPE3/CB97	1.878	11.5	91-103
LDCAL5/CB95	1.821	11.6	81-89
HDPE5/CB95	1.793	11.5	80-86
LDPE5/CB95	1.790	11.3	71-79
RAP	2.001	10.8	20-26
LDCAL3/RAP97	1.965	10.0	14-19
HDPE3/RAP97	1.926	9.9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

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

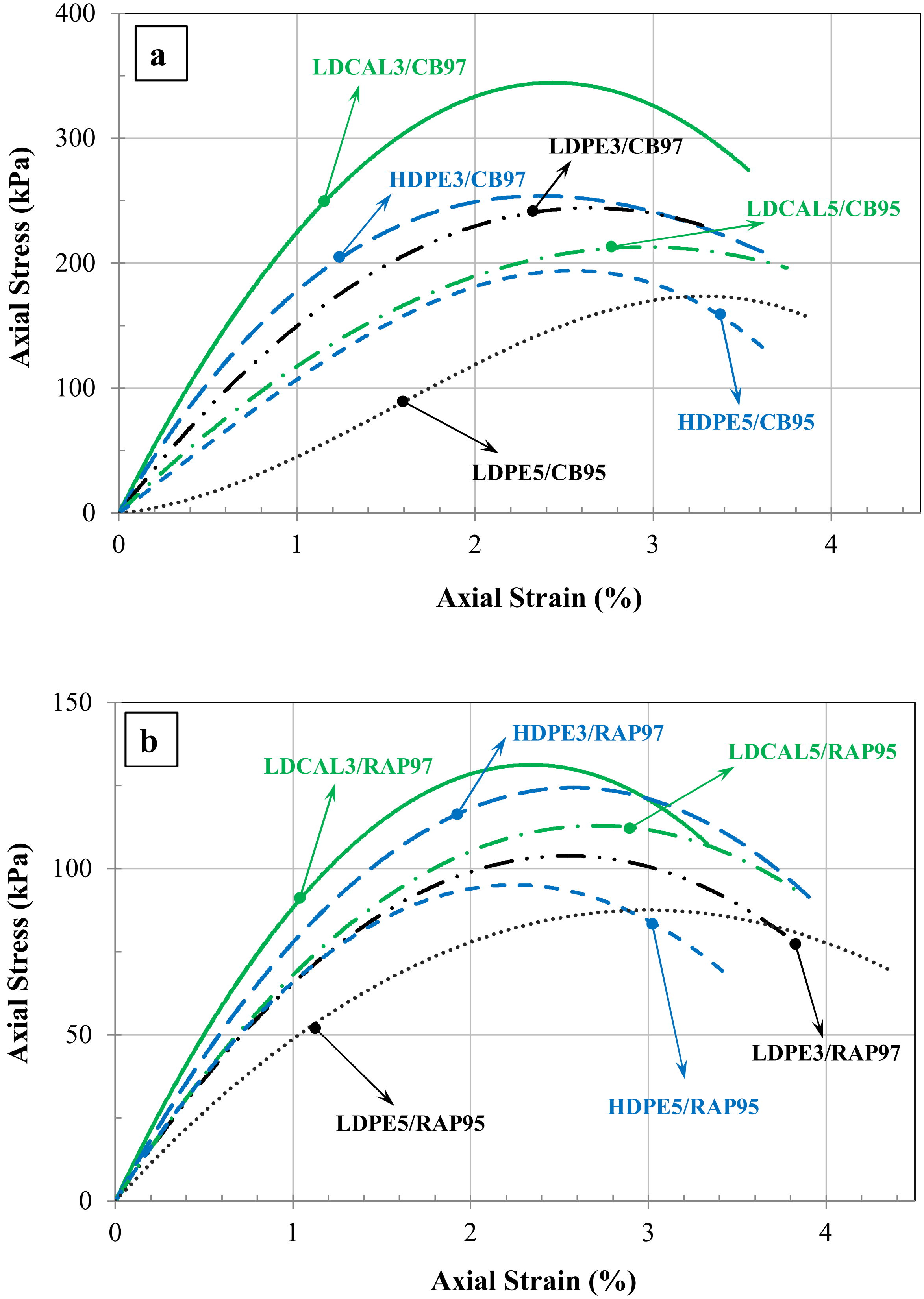
Blend	E (MPa)	E_{50} (MPa)
LDCAL3/CB97	25.0	23.9
HDPE3/CB97	20.0	19.7
LDPE3/CB97	16.7	15.6
LDCAL5/CB95	12.5	12.0
HDPE5/CB95	10.8	10.7
LDPE5/CB95	6.9	5.6
LDCAL3/RAP97	10.0	9.4
HDPE3/RAP97	8.3	8.3
LDPE3/RAP97	7.7	7.5
LDCAL5/RAP95	7.8	6.8
HDPE5/RAP95	6.9	6.9
LDPE5/RAP95	5.0	4.9



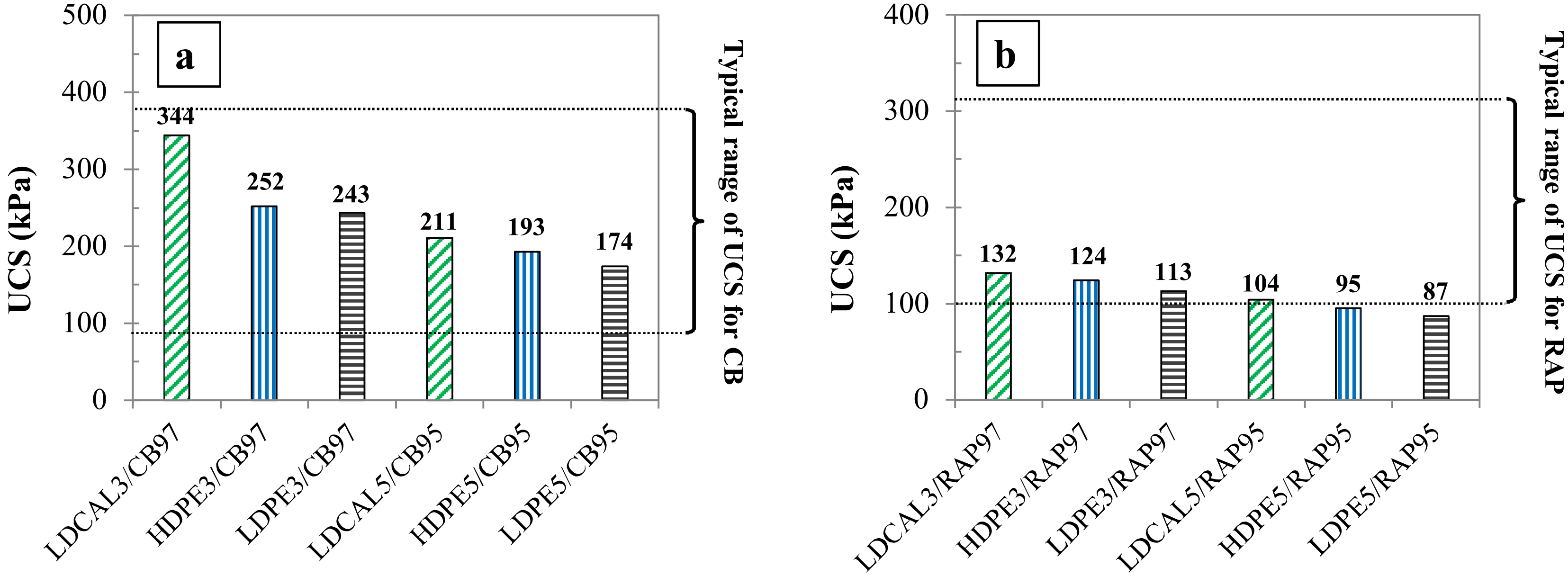
Percent Passing (%)
100
80
60
40
20
0
0.00
0.01
0.10
1.00
10.00
100.00
Particle size (mm)
LDCAL
HDPE
LDPE
LDCAL
HDPE
LDPE
CB
RAP



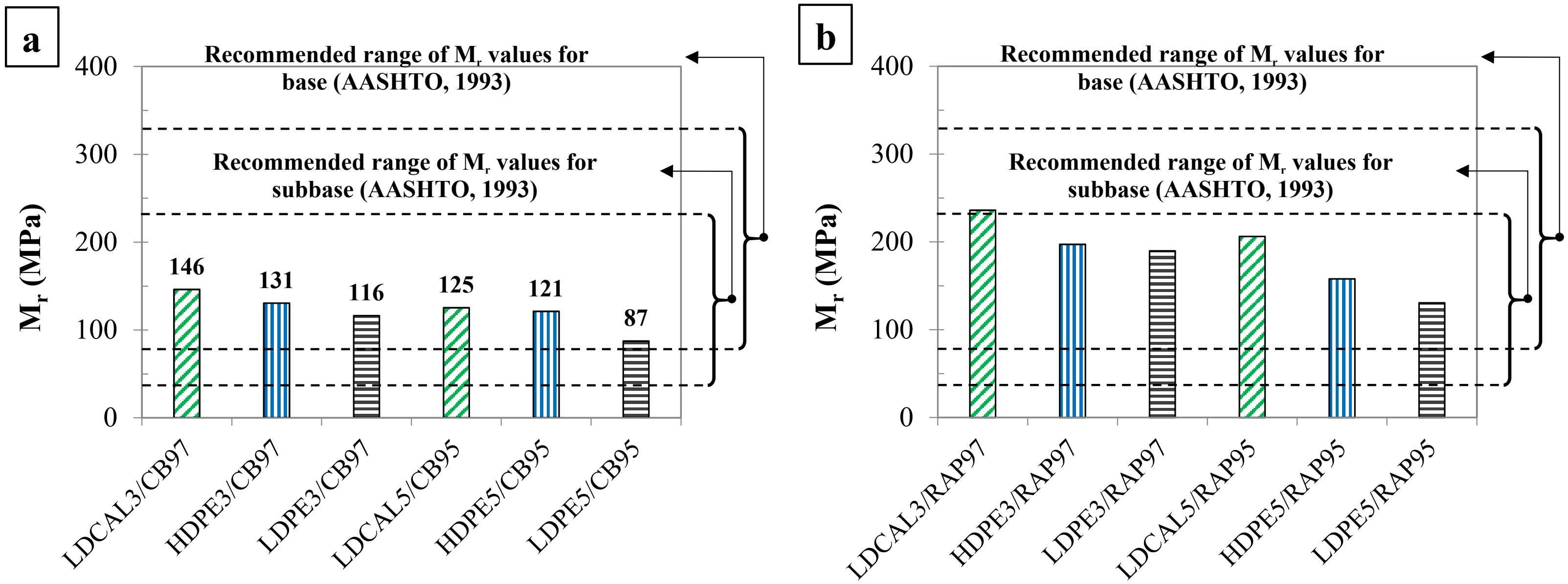
"n" exponent
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.484
0.489
0.490
0.490
0.493
0.494
0.494
0.543
0.547
0.548
0.548
0.550
0.552
0.551
Control CB
LDCAL3/CB97
HDPE3/CB97
LDPE3/CB97
LDCAL5/CB95
HDPE5/CB95
LDPE5/CB95
Control RAP
LDCAL3/RAP97
HDPE3/RAP97
LDPE3/RAP97
LDCAL5/RAP95
HDPE5/RAP95
LDPE5/RAP95
Plastics/CB Blends
Plastics/RAP Blends
Range of ASTM D1241 Type C Gradation

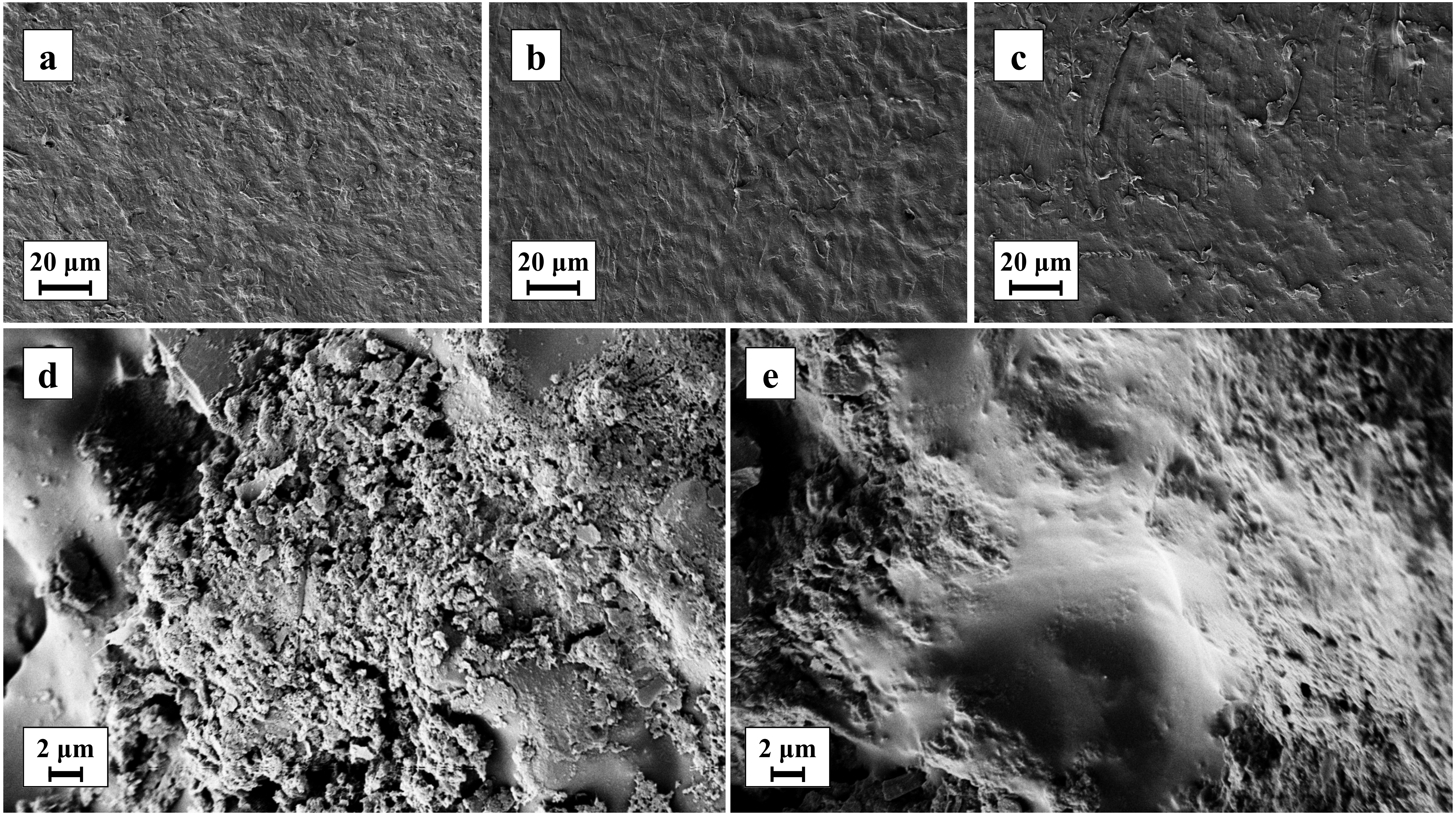


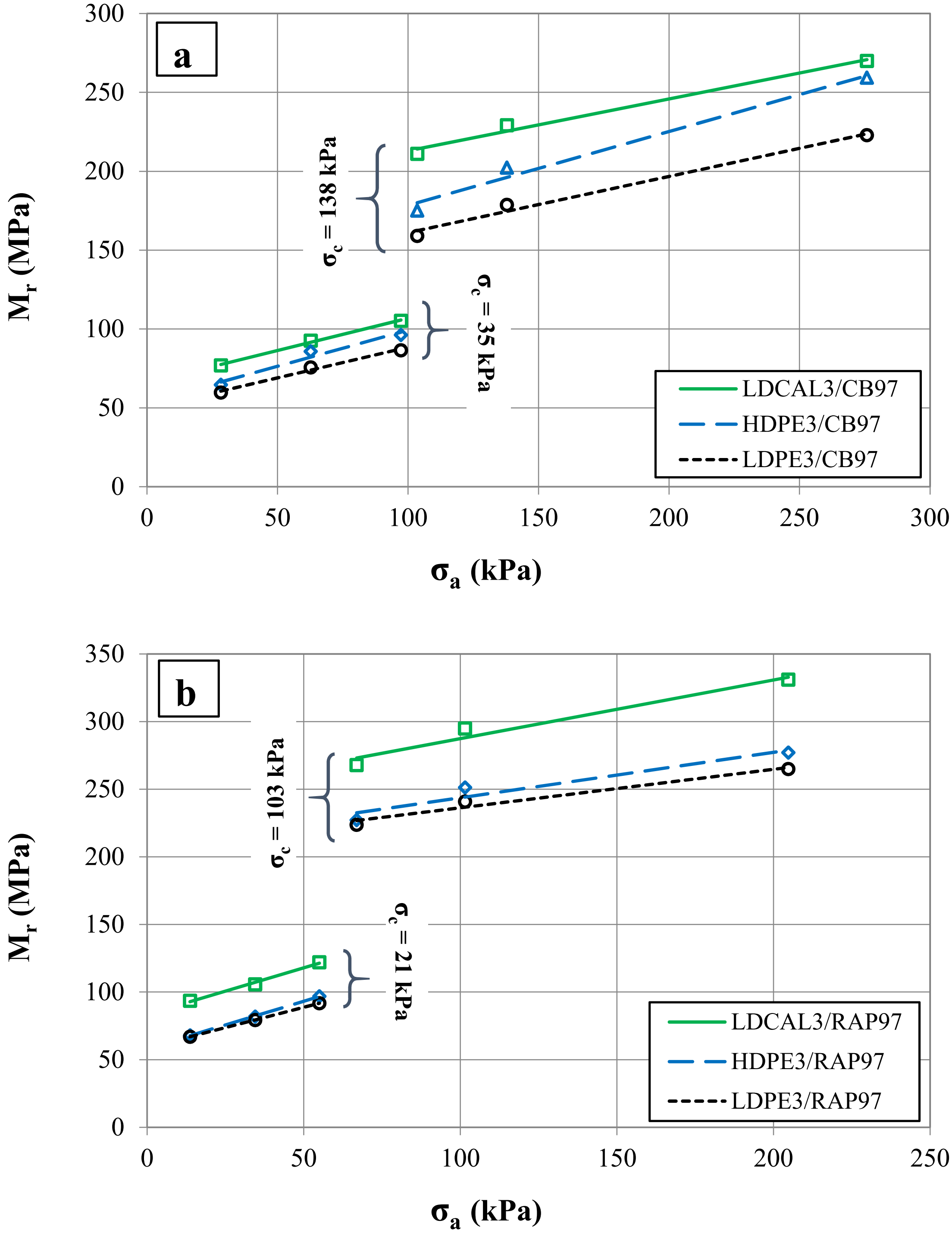
a
Axial Stress (kPa)
Axial Strain (%)
400
300
200
100
0
0
1
2
3
4
LDCAL3/CB97
LDPE3/CB97
HDPE3/CB97
LDCAL5/CB95
HDPE5/CB95
LDPE5/CB95
b
Axial Stress (kPa)
Axial Strain (%)
150
100
50
0
0
1
2
3
4
HDPE3/RAP97
LDCAL5/RAP95
LDCAL3/RAP97
LDPE3/RAP97
HDPE5/RAP95
LDPE5/RAP95

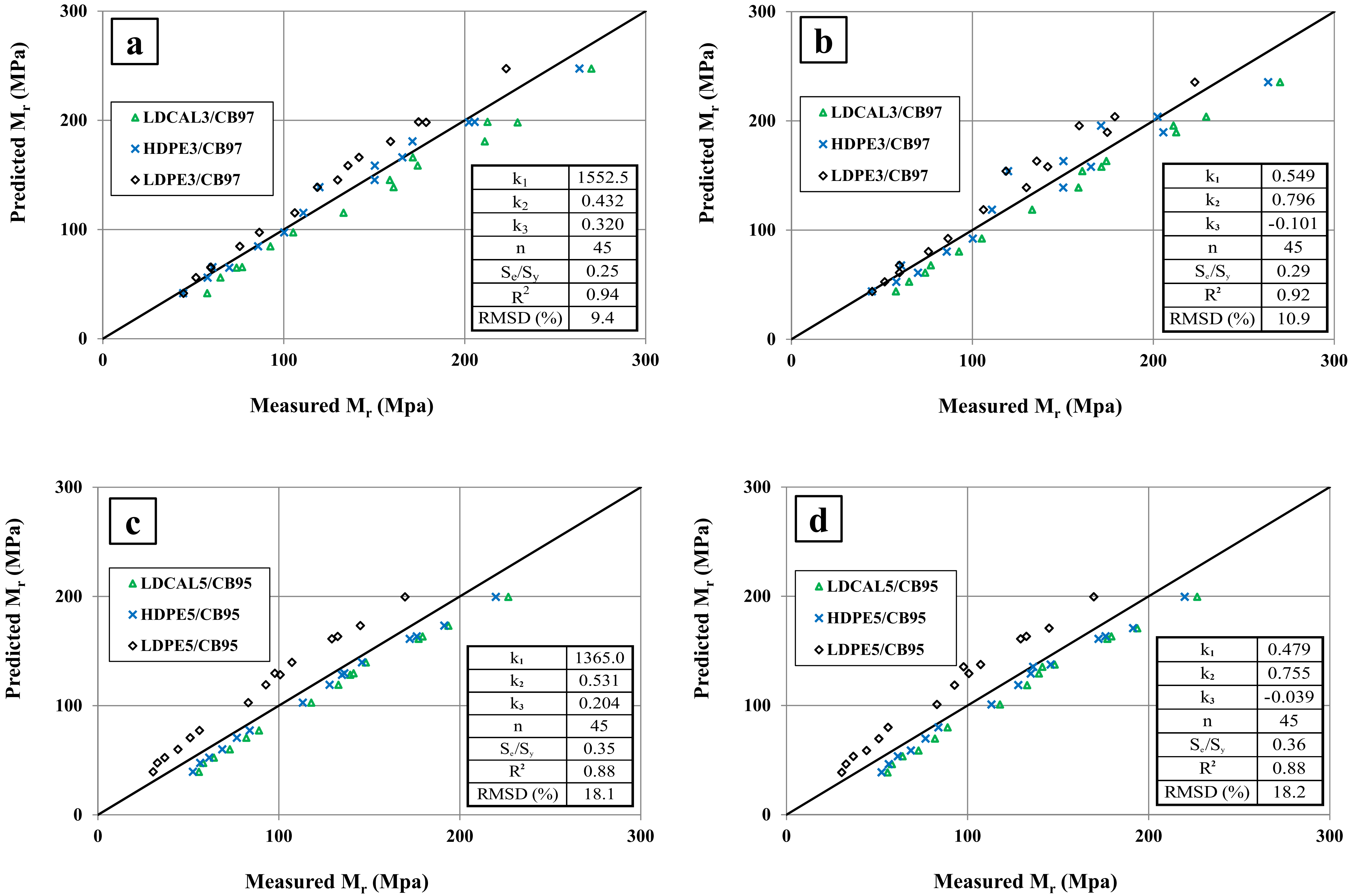


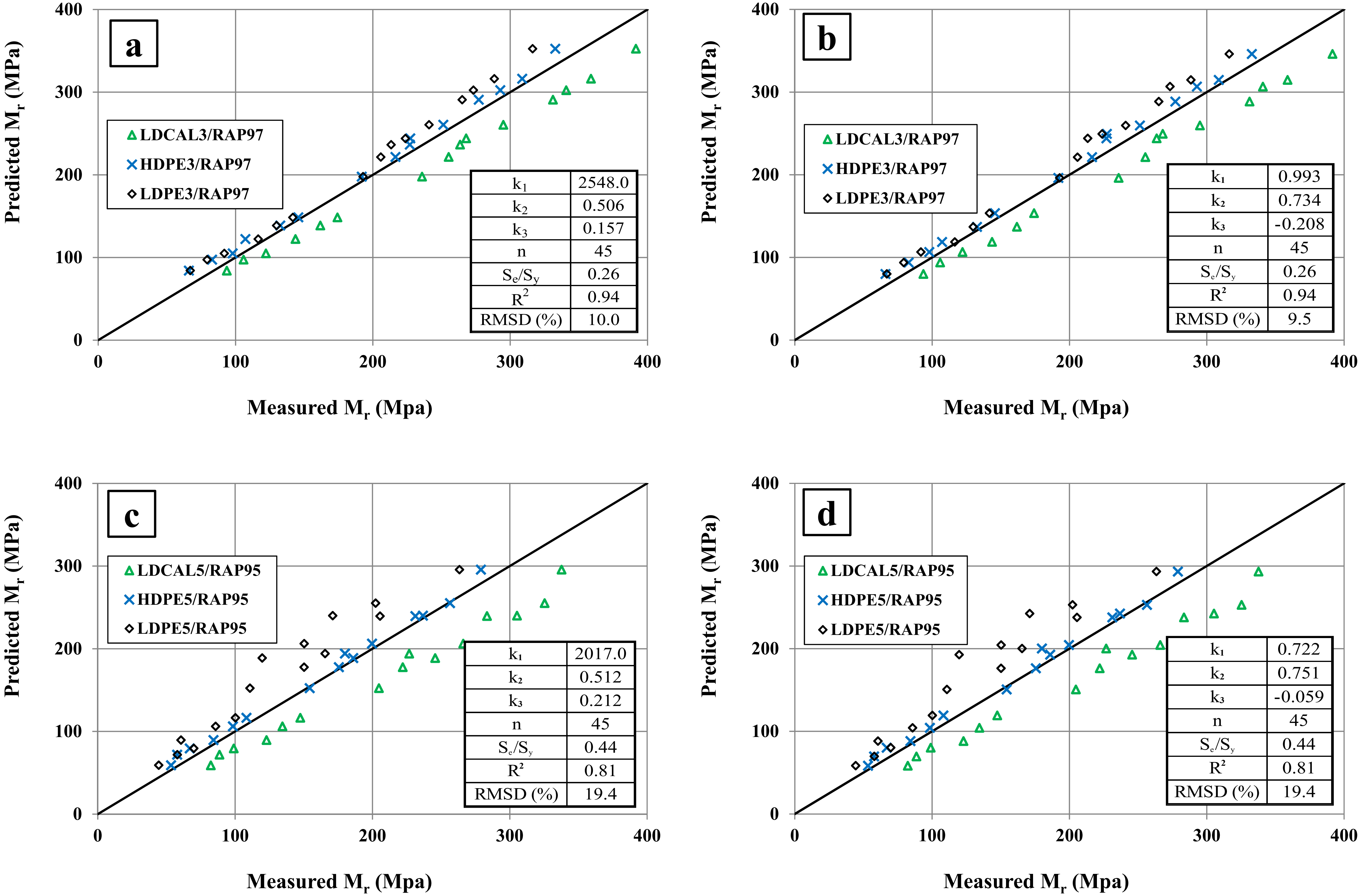
a
UCS (kPa)
500
400
300
200
100
0
344
252
243
211
193
174
Typical range of UCS for CB
LDCAL3/CB97
HDPE3/CB97
LDPE3/CB97
LDCAL5/CB95
HDPE5/CB95
LDPE5/CB95
b
400
300
200
100
0
132
124
113
104
95
87
Typical range of UCS for RAP
LDCAL3/RAP97
HDPE3/RAP97
LDPE3/RAP97
LDCAL5/RAP95
HDPE5/RAP95
LDPE5/RAP95


a
b
Recommended range of M_r values for base (AASHTO, 1993)
Recommended range of M_r values for subbase (AASHTO, 1993)
M_r (MPa)
400
300
200
100
0
146
131
116
125
121
87
LDCAL3/CB97
HDPE3/CB97
LDPE3/CB97
LDCAL5/CB95
HDPE5/CB95
LDPE5/CB95
LDCAL3/RAP97
HDPE3/RAP97
LDPE3/RAP97
LDCAL5/RAP95
HDPE5/RAP95
LDPE5/RAP95


a
20 µm
b
20 µm
c
20 µm
d
2 µm
e
2 µm


a
b
M_r (MPa)
σ_a (kPa)
σ_c = 138 kPa
σ_c = 35 kPa
σ_c = 103 kPa
σ_c = 21 kPa
LDCAL3/CB97
HDPE3/CB97
LDPE3/CB97
LDCAL3/RAP97
HDPE3/RAP97
LDPE3/RAP97


a
LDCAL3/CB97
HDPE3/CB97
LDPE3/CB97
k1 1552.5
k2 0.432
k3 0.320
n 45
Se/Sy 0.25
R2 0.94
RMSD (%) 9.4
b
LDCAL3/CB97
HDPE3/CB97
LDPE3/CB97
k1 0.549
k2 0.796
k3 -0.101
n 45
Se/Sy 0.29
R2 0.92
RMSD (%) 10.9
c
LDCAL5/CB95
HDPE5/CB95
LDPE5/CB95
k1 1365.0
k2 0.531
k3 0.204
n 45
Se/Sy 0.35
R2 0.88
RMSD (%) 18.1
d
LDCAL5/CB95
HDPE5/CB95
LDPE5/CB95
k1 0.479
k2 0.755
k3 -0.039
n 45
Se/Sy 0.36
R2 0.88
RMSD (%) 18.2
Predicted Mr (MPa)
Measured Mr (Mpa)
0
100
200
300



a
b
c
d
LDCAL3/RAP97
HDPE3/RAP97
LDPE3/RAP97
LDCAL5/RAP95
HDPE5/RAP95
LDPE5/RAP95
Predicted M_r (MPa)
Measured M_r (Mpa)
0
100
200
300
400
a: 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: 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: 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: 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