Stiffness Properties of Recycled Concrete Aggregate with Polyethylene Plastic Granules in Unbound Pavement Applications

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Abstract

The growing population in the modern world has resulted in an increase in waste generation and stockpiles. There have been increasing concerns on how to sustainably reuse wastes in civil and geotechnical engineering applications. Two major municipal waste streams are plastic wastes and Recycled Concrete Aggregates (RCA) generated by demolition activities. A potential application for growing stockpiles of plastic and RCA wastes is in the construction of roads, as pavement base/subbases typically demand significant quantities of construction materials. In this research, RCA was blended with Low Density Polyethylene (LDPE) and High Density Polyethylene (HDPE) plastics. A range of geotechnical tests such as California Bearing Ratio (CBR), Unconfined Compressive Strength (UCS), and Repeated Load Triaxial (RLT) tests were conducted on RCA/HDPE and RCA/LDPE blends. Comparison of CBR, UCS and RLT results with those of typical quarry materials indicated that RCA/HDPE and RCA/LDPE can be used sustainably in the construction of pavement base/subbase layers. RLT testing results were further evaluated using resilient moduli models, to characterize the RCA/HDPE and RCA/LDPE performances under simulated traffic loads.

Keywords: Stiffness, Resilient Modulus, Recycled Materials, Polyethylene Plastic, Pavement Subbase, Pavement Base

Introduction

The high living standards and growing population in the modern world has led to an increasing amount of waste production. Consequently, waste management has become a serious concern globally (Choudhary et al. 2014). The conventional approach of waste management is landfilling. However, this is not a proper solution due to many drawbacks such as high landfilling costs and limited availability of land in many countries (Choudhary et al. 2014). As a result, the need for other solutions for management of wastes is required. One of these approaches is the application of waste materials in industries in which substantial amount of materials is required, such as in civil engineering applications, and in road pavement construction. However, usage of wastes in pavement bases/subbases requires sufficient knowledge about the engineering and geotechnical properties of these waste materials.

Annually, approximately 190 million tonnes of plastics is produced in the world, of which 66 million tonnes is polyethylene. As an average, 8-12% of the total municipal waste stream consists of plastics. This percentage varies from country to country, depending on factors, such as lifestyle, quality of life and income level (Wong et al. 2015). In Australia, this percentage is estimated to be about 16%, with an annual production of plastics waste of 2.24 million tons in 2008 (Bajracharya et al. 2016). Production of plastics has increased annually due to the population growth and industrial applications as well as its low production cost. Plastic wastes are a prime contributor to the increasing amounts of municipal waste (Meran et al. 2008). Two products of the plastic industries are Low Density Polyethylene (LDPE) and High Density Polyethylene (HDPE). HDPE is stiffer, higher in tensile strength, and better in heat resistance, while LDPE is more flexible (Schwartz 2002). The mechanical properties of HDPE and LDPE including elongation and tensile strength have been reported by Meran et al. (2008). Research on reinforcing civil engineering material with HDPE dates back to early 1990s when Benson and Khire (1994) reinforced sand with HDPE strips and evaluated the geotechnical properties of the reinforced blends. Reinforcement was shown to improve the California Bearing Ratio (CBR), secant modulus, resilient modulus and shear strength of the sand. Studies have been undertaken on using HDPE in form of strips as reinforcement for pavement material in the subbase layer (Choudhary et al. 2014) and subgrades (Choudhary et al. 2010). Test results showed improvement in some of the geotechnical properties, such as bearing capacity and secant modulus of the specimens reinforced by HDPE strips. Another study conducted by Jha et al. (2014) showed that application of HDPE strips enhanced the bearing capacity of industrial wastes in pavement applications, and in flexible pavement construction. Evidently, only a few studies have been done on LDPE, and studies on HDPE have used this material, solely in form of strips or fibers.

Demolition activities are a major factor that results in increasing stockpiles of construction and demolition wastes, including Recycled Concrete Aggregate (RCA), crushed brick, recycled asphalt pavement and recycled glass (Arulrajah et al. 2014; Disfani et al. 2014). Application of these materials in civil engineering construction projects were carried out recently by several researchers, including Arulrajah et al. (2013 a), Gómez-Soberón (2002), McKelvey et al. (2002), Poon and Chan (2006), Paranavithana and Mohajerani (2006), Courard et al. (2010) and Rahman et al. (2014). RCA properties are more superior to typical quarry materials when used in the construction of pavement layers (Arulrajah et al. 2014). This material was selected to be blended with LDPE and HDPE granules in this research.

The granules are raw products of plastic recycling industries, and no further procedure is done to turn them into strips of fibers. The aim is to investigate the applicability of these granules in pavement base/subbase applications to reduce the need for landfilling. However, since the polyethylene plastic in this research is intended to be used in form of granules instead of reinforcing fibers, slight degradation of RCA properties is expected. Hence, a range of geotechnical tests were conducted to evaluate the mechanical properties of the blends of

RCA/HDP and RCA/LDPE, especially in terms of stiffness and resilient modulus. HDPE and LDPE plastics granules used were processed by-products obtained from plastic recycling. Application of the processed granule products, if the requirements are met, is important since it saves costs and effort needs to be spent to convert them into fibers or strips, but at the same time fulfills the aim of reusing the waste plastics instead of dumping these in landfills. Accordingly, a range of geotechnical tests were conducted to evaluate the mechanical and stiffness properties of RCA/HDPE and RCA/LDPE blends. The concept used, in terms of using RCA in blends with HDPE or LDPE for pavement base/subbase applications is novel and will lead to a significant reduction of these waste materials being landfilled.

Materials and Methods

The materials used in this research included RCA blended with HDPE and LDPE granules. These were provided from recycling industries in Victoria, Australia. **Table 1** presents the properties of these waste materials.

Figure 1 shows the particle size distribution of RCA, as well as blends of RCA with 3% and 5% of HDPE and LDPE contents. Evidently, the plastics contents did not cause significant changes in the particle size distribution of the blends. **Figure 1** also shows images of HDPE and LDPE granules.

Modified proctor method according to ASTM-D1557 (2012) was used to determine the Optimum Moisture Content (OMC) and Maximum Dry Density (MDD) of the blends. In this regard, specimens were compacted in five layers, each layer under 56 blows of the hammer, in a mold with the diameter of 152.4 mm and height of 116.43 mm. Dry density versus moisture content curves were then drawn in order to obtain the OMC and MDD of the blends. In order to avoid segregation, care was taken when placing material for each layer in the mold, by keeping the scoop as close as possible inside the mold when pouring the material. Also, in order to examine the uniformity of the mixtures, one scoop of the blends was extracted and spread on the table in a circular shape, dividing the material into 4 equal portions followed by observing and comparing the quarters visually. No significant difference in the plastic content of each quarter was observed.

Using the obtained OMC and plastic content of 5%, CBR samples were prepared in a 152.4 mm diameter mold in five layers each compacted under modified effort using 56 blows according to ASTM-D1883 (2014). In this research, plastic contents were selected so that CBR values of the blends would meet road authorities’ requirements, which specify a CBR greater than 80 for subbases and greater than 100 for bases. First, blends with plastic content of 5% were prepared for determination of OMC. Then using the obtained values of OMC, CBR samples were prepared and compacted. Based on obtained CBR values another plastic content, being 3% was proposed.

Results of the compaction and CBR tests on blends of 95% RCA and 5% HDPE/LDPE are presented in **Table 2**. Obviously, blending RCA with plastic granules with a low specific gravity resulted in a low MDD. CBR values corresponding to 2.54 mm penetration for both blends are about 100, which is the limit for pavement base layer application. As a result, in order not to reach a CBR value lower than the authorities’ requirements for applicability in pavement base/subbase layers, blends of RCA with 5 and a lower plastic content, i.e., 3% were selected as the following: RCA95/HDPE5, RCA5/LDPE5, RCA97/HDPE3, and RCA97/LDPE3. Also, in order to investigate the result of introducing these plastic granules, all tests were conducted on pure RCA as well. The lower limit of CBR for typical quarry material is 80% (Arulrajah et al. 2013 b). Results of modified compaction and CBR tests on the RCA97/HDPE3, and RCA97/LDPE3, as well as pure RCA are presented in **Table 2**.

Resilient modulus (M_r) is an important parameter required for structural design of pavement layers. Hence, investigation of the changes in resilient behavior of the blends by adding particles of HDPE and LDPE was also evaluated. Resilient characteristics of the specimens were determined using Repeated Load Triaxial (RLT) tests. RLT test is meant to simulate the pavement layer's condition under repeated traffic loads (AASHTO-T307-99 2007). Resilient modulus (M_r) is the ratio of a repeated axial stress to the recoverable axial strain caused by the repeated load. In RLT testing procedure, a haversine-shaped loading pulse with 0.1 s loading period and 0.9 s resting period was applied (AASHTO-T307-99 2007). A triaxial cell was used with the universal testing machine to carry out the RLT tests. A split compaction mold with a diameter of 100 mm and height of 202 mm was used to prepare RLT specimens. Specimens prepared with impact method were compacted in 8 layers, following the procedure described in ASTM-D1557 (2012). A collar was used to ensure the aggregates remain inside the mold while compacting the top layers. Materials were placed inside the mold carefully to avoid segregation. During the tests, specimens were protected from moisture change by using a latex membrane. A total of 60 data sets for M_r values was obtained from a range of repeated vertical stress and static confinements in 15 sequences of RLT testing procedure. Two popular three-parameter resilient modulus prediction models were selected to evaluate the data obtained from laboratory tests. The two models used were Puppala et al. (1997) and AASHTO (2002). Though there are many other methods available, these were selected since their input data was available and these were suitable for granular material applications.

Unconfined Compressive Strength (UCS) test was carried out to determine stiffness characteristics of the compacted specimens. UCS test is a popular testing procedure for evaluation of pavement material. Since RLT testing is a nondestructive procedure, the same specimens after completion of RLT testing were used for the UCS tests. In addition to measuring UCS values, Young's modulus (E) and secant modulus (E_{50}) were determined from the UCS tests. E is the ratio on the stress versus strain curve at the elastic zone where the strains are recoverable. E_{50} is the slope of the line that is drawn from the origin to the stress at half of the UCS peak value on the stress-strain curve. Lateral displacement was measured using three lateral LVDTs mounted in the triaxial cell, forming 120° angles and pointing to the mid-height of the specimen, to determine Poisson's ratio (ν). Poisson's ratio is defined as the ratio of lateral strain to axial stain under axial loading in the elastic zone of the axial stress-axial strain curve and specifies the extent to which a specimen can be compressed (Thom 2008). **Figure 2** shows the specimens prepared for UCS and RLT tests using 3% and 5% of HDPE. The HDPE particles are more visible in the specimen with 5% HDPE than in the 3% HDPE.

Results and Discussion

The stress-strain curves of the four blends obtained from UCS testing is illustrated in **Figure 3**. Evidently, an increase in the plastic content of the specimens results in a reduction of UCS values. This can be attributed to the fact that plastic particles have smoother surfaces compared with RCA particles, hence, more plastic granules result in less surface roughness, which tend to result in subsequent higher stiffness (Cheung and Dawson 2002). **Figure 3** also shows that blends of RCA/HDPE have higher UCS values. This may be related to the greater sphericity of HDPE particles compared with that of LDPE particles.

Young's Modulus (E) and secant modulus at half of the UCS value (E_{50}) were obtained from the graphs of **Figure 3**. These two important parameters used in geotechnical engineering and pavement analyses. From the results of the lateral LVDTs, Poisson's ratio (ν) of the blends were evaluated. Values of void ratio, E, E_{50} and ν are presented in **Table 3**. RCA/HDPE specimens showed higher E, which means lower elastic displacement under the same stress level, compared with RCA/LDPE specimens. Secant modulus and Poisson's ratio of the RCA/HDPE blends are also found to have higher values. Poisson's ratios (ν) obtained for all blends fall between the typical ranges of 0.15 to 0.35 specified for sand and gravel (Das 2008). Results of Table 3 also show that increasing the plastic content results in decrease in the ν values. Poisson's ratio is obtained from data corresponding to the elastic zone of stress-strain curves of the blends (Figure 3). This zone for all blends of this research fell between stress levels of approximately 50 kPa to 100 kPa. Low E values for blends with high plastic content results in greater axial strain under the same stress as blends with low plastic content. Low ν values in blends with low plastic content shows that the lateral strains do not correspondingly increase. This can be attributed to low structure integrity of these blends due to high content of particles with smooth surfaces (plastic particles).

Figures 4 and 5 show the resilient modulus versus maximum axial stress graphs for RCA/HDPE and RCA/LDPE blends, respectively. As illustrated in the graphs, a high confining pressure results in a high resilient modulus. This can be explained by the fact that the high confinement increases the aggregate interlocking, which results in low strains and accordingly low M_r values. Thach Nguyen and Mohajerani (2016) explained the effect of confining pressure through predictive resilient modulus models. **Figures 4 and 5** also indicate that under the same confining pressure, increases in deviator (axial) stress which result in higher M_r values. This can be attributed to greater stress hardening under greater deviatoric stresses (Puppala et al. 2011). However, high deviatoric stress can also result in low M_r values (Thach Nguyen and Mohajerani 2016) which is not the case in this research.

Aside from the effects of testing conditions (deviator and confining pressures), the RLT results showed that in both RCA/HDPE and RCA/LDPE blends, the M_r values decreased by increasing the plastic content. This, together with UCS values, is further illustrated in **Figure 6**. Values of M_r presented in **Figure 6 (b)** are the average of resilient moduli obtained from 15 sequences of the RLT test. **Figure 6** also compares the RCA/plastic results with typical UCS values reported previously for RCA (Arulrajah et al. 2014) and recommended ranges of M_r values for bases/subbases (AASHTO (1993). High roughness of aggregate surfaces is known to result in greater resilient modulus (Barksdale and Itani 1989; Lekarp et al. 2000). As a result, replacing more rough particles of RCA with rather smooth surfaced particles of HDPE or LDPE reduces the resilient modulus. Also, blends of RCA/HDPE showed greater M_r values compared to the other type of blends. This can be explained by observing the Young's moduli (E) presented in **Table 3**. This modulus is in fact the slope of stress-strain curve at the elastic zone, where the strains are recoverable. Under the same stress, a high E value means a low recoverable strain and accordingly a high resilient modulus.

Two other factors that can cause high M_r values of RCA/HDPE compared with those of RCA/LDPE are particle shape and particle roughness. In terms of particle roughness, Scanning Electron Micrograph (SEM) was employed to characterize the particle surface. **Figure 7** presents SEM images of HDPE and LDPE plastic granules indicating their smooth surfaces. These are 1000X magnified micrographs of HDPE and LDPE. Clearly, there is no significant difference in surface roughness of these two particles, which means that the surface roughness is not the reason for different M_r values of the RCA/HDPE and RCA/LDPE specimens. On the other hand, the close-up image of the two particles illustrated in **Figure 7**, shows that HDPE particles generally have greater sphericity compared to LDPE particles. Low sphericity of particles is known to degrade resilient properties of pavement layers (Nataatmadja and Tan 2001). Overall, M_r values of the four specimen types are within the expected M_r values for typical quarry materials at 90% of OMC, which is 150 to 300 MPa (Arulrajah et al. 2013 b).

Figure 8 (a) presents the relationship between E and E_{50} moduli and Figure **8 (b)** presents the relationship between Mr and UCS values for the RCA/Plastics blends. The range between the upper and lower envelopes of both plots is noticeably limited. The Young's Modulus of pure RCA is 1.15 times of its secant modulus, and the resilient modulus (in MPa) is 0.58 times of the UCS value (in kPa) of pure RCA. These are found to be close to the lower range of the relationships presented in **Figure 8**.

The 60 data sets obtained from RLT testing procedure were evaluated through two predictive resilient modulus models, suggested by Puppala et al. (1997), also known as octahedral stress state model, and AASHTO (2002), also known as modified universal model. These models are presented in Equations 1 and 2, respectively:

$$M_r = p_a[k_1(\frac{\sigma_3}{p_a})^{k_2}(\frac{\sigma_d}{p_a})^{k_3}] \quad (1)$$

$$M_r = k_1 p_a \left(\frac{\sigma_b}{p_a}\right)^{k_2} (\frac{\tau_{oct}}{p_a} + 1)^{k_3} \quad (2)$$

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

Figure 9 compares the predicted with measured resilient modulus using these predictive models and also presents the model parameters obtained from regression analysis of the 60 data sets undertaken in this research. Model parameters k_1, k_2 and k_3 correspond to the Puppala et al. (1997) model (Equation 1). k_1 and k_2 are positive since an increase in σ_3 and σ_d results in a corresponding increase in M_r, as evident in **Figures 4** and **5**, while k_3 is positive since M_r is always a positive value. k_1 and k_2 parameters corresponding to the modified universal model (Equation 2) are also positive due to similar reasons. However, k_3 is negative of which an increase in octahedral shear stress results in a corresponding decrease in the M_r value. This is due to the fact that an increase in shear stress softens the specimen and results in a low resilient modulus. Comparison between k parameters obtained from blends with and without plastic shows an increase in k_2 and k_3 (absolute value of k3 in AASHTO (2002) model) in both models by introducing plastic particles to RCA. This indicates that sensitivity of the models to confining stress, bulk stress, deviator stress and octahedral shear stress is increased by adding plastic particles.

Three statistical measurements were used in order to evaluate the goodness of fit of test data in the models. These include: standard accuracy (S_e/S_y), coefficient of determination (R^2), and Root Mean Square Deviation (RMSD). In these measures, S_e is standard error of estimate and S_y is the standard deviation (Azam et al. 2013; Witczak et al. 2002). For evaluation of accuracy of fit, Witczak et al. (2002) criterion was used. In this criterion, $S_e/S_y \leq 0.35$ and $R^2 \geq 90$ represent "Excellent", $0.36 \leq S_e/S_y \leq 0.55$ and $0.70 \leq R^2 \leq 0.89$ represent "Good", $0.56 \leq S_e/S_y \leq 0.75$ and $0.40 \leq R^2 \leq 0.69$ represent "Fair", and $0.76 \leq S_e/S_y \leq 0.90$ and $0.20 \leq R^2 \leq 0.39$ represent "Poor" fit. Statistical measurements calculated and presented in **Figure 9** show that test data show an "Excellent" fit for both of these models. This means that resilient behavior of these blends can be evaluated or predicted through these established models, in spite of existence of plastic granules in them.

Conclusions

In this research, two types of recycled waste materials, being RCA and with polyethylene plastic blends (HDPE and LDPE) were evaluated for their stiffness and resilient characteristics. Since the polyethylene plastics in this research were used in form of granules instead of reinforcing fibers, slight degradation of RCA properties was observed. The following results are obtained from the outcomes of this research:

1- Samples prepared by adding 3% and 5% LDPE or HDPE indicated CBR values comparable to that of typical quarry materials, and these blends could be used in base/subbase layers. Blends of RCA/HDPE showed a higher CBR values.
2- Specimens containing HDPE particles showed greater UCS values and higher Young's modulus compared with LDPE blends. SEM images showed there was no significant

difference in roughness of HDPE and LDPE particle surfaces, this could be attributed to lower sphericity of LDPE particle compared with cylindrical shape of HDPE particles. Generally, a greater plastic content results in lower stiffness parameters of specimens, including E, E_{50} and ν values.

3- RCA/HDPE specimens presented higher resilient modulus, due to higher E values and also, its cylindrical shape of HDPE particles. Similar to stiffness parameters, M_r values of the specimens decreased by increasing the plastic content, due to further replacement of rough-surfaced materials (RCA) with smooth-surfaced particles (HDPE/LDPE).

4- RLT test results showed that M_r values of all the 4 types of specimen fall within the range of typical quarry materials. Moreover, the evaluation of the results using the resilient modulus models showed that this percentage of plastic particles did not affect the geotechnical nature of RCA. As a result, RCA/HDPE and RCA/LDPE blends can be used in pavement bases/subbases.

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References

AASHTO-T307-99 (2007). "Standard Method of Test for Determining the Resilient Modulus of Soils and Aggregate Materials." American Association of State Highway and Transportation Officials, Washington, DC.

AASHTO (1993). *AASHTO Guide for Design of Pavement Structures, 1993*, American Association of State Highway

Transportation Officials.

AASHTO (2002). "Guide for Design of New and Rehabilitated Pavement Structures." National Cooperative Highway Research Program, American Association of State Highway and Transportation Officials, Washington, D.C.

Arulrajah, A., Disfani, M. M., Horpibulsuk, S., Suksiripattanapong, C., and Prongmanee, N. (2014). "Physical Properties and Shear Strength Responses of Recycled Construction and Demolition Materials in Unbound Pavement Base/Subbase Applications." *Construction and Building Materials*, 58, 245-257.

Arulrajah, A., Piratheepan, J., and Disfani, M. M. (2014). "Reclaimed asphalt pavement and recycled concrete aggregate blends in pavement subbases: Laboratory and field evaluation." *Journal of Materials in Civil Engineering*, 26(2), 349-357.

Arulrajah, A., Piratheepan, J., Disfani, M. M., and Bo, M. W. (2013 a). "Resilient Moduli Response of Recycled Construction and Demolition Materials in Pavement Subbase Applications." *Journal of Materials in Civil Engineering*, 25(12), 1920-1928.

Arulrajah, A., Piratheepan, J., Disfani, M. M., and Bo, M. W. (2013 b). "Geotechnical and Geoenvironmental Properties of Recycled Construction and Demolition Materials in Pavement Subbase Applications." *Journal of Materials in Civil Engineering*, 25(8), 1077-1088.

ASTM-D1557 (2012). "Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Modified Effort (56,000 ft-lbf/ft3 (2,700 kN-m/m^3))." ASTM International, West Conshohocken, PA.

ASTM-D1883 (2014). "Standard Test Method for CBR (California Bearing Ratio) of Laboratory-Compacted Soils." *West Conshohocken, PA: ASTM International*.

Azam, A. M., Cameron, D. A., and Rahman, M. M. (2013). "Model for Prediction of Resilient Modulus Incorporating Matric Suction for Recycled Unbound Granular Materials." *Can Geotech J*, 50(11), 1143-1158.

Bajracharya, R. M., Manalo, A. C., Karunasena, W., and Lau, K.-t. (2016). "Characterisation of recycled mixed plastic solid wastes: Coupon and full-scale investigation." *Waste Management*, 48, 72-80.

Barksdale, R. D., and Itani, S. Y. (1989). "Influence of Aggregate Shape on Base Behavior." *Transp Res Record*(1227), 173-182.

Benson, C. H., and Khire, M. V. (1994). "Reinforcing sand with strips of reclaimed high-density polyethylene." *Journal of Geotechnical Engineering*, 120(5), 838-855.

Cheung, L. W., and Dawson, A. (2002). "Effects of particle and mix characteristics on performance of some granular materials." *Transportation Research Record: Journal of the Transportation Research Board*(1787), 90-98.

Choudhary, A., Jha, J., and Gill, K. (2010). "Utilization of plastic wastes for improving the sub-grades in flexible pavements." *Paving Materials and Pavement Analysis*, 320-326.

Choudhary, A., Jha, J., Gill, K., and Shukla, S. K. (2014). "Utilization of fly ash and waste recycled product reinforced with plastic wastes as construction materials in flexible pavement." *Proceedings of Geo-Congress*, 3890-3902.

Courard, L., Michel, F., and Delhez, P. (2010). "Use of concrete road recycled aggregates for Roller Compacted Concrete." *Construction and Building Materials*, 24(3), 390-395.

Das, B. M. (2008). *Advanced Soil Mechanics*, Taylor & Francis, London.

Disfani, M. M., Arulrajah, A., Haghighi, H., Mohammadinia, A., and Horpibulsuk, S. (2014). "Flexural beam fatigue strength evaluation of crushed brick as a supplementary material in cement stabilized recycled concrete aggregates." *Construction and Building Materials*, 68, 667-676.

Gómez-Soberón, J. M. V. (2002). "Porosity of recycled concrete with substitution of recycled concrete aggregate: An experimental study." *Cement and Concrete Research*, 32(8), 1301-1311.

Jha, J., Choudhary, A., Gill, K., and Shukla, S. K. (2014). "Behavior of plastic waste fiber-reinforced industrial wastes in pavement applications." *International Journal of Geotechnical Engineering*, 8(3), 277-286.

Lekarp, F., Isacsson, U., and Dawson, A. (2000). "State of the Art. I: Resilient Response of Unbound Aggregates." *Journal of Transportation Engineering*, 126(1), 66-75.

McKelvey, D., Sivakumar, V., Bell, A., and McLaverty, G. (2002). "Shear strength of recycled construction materials intended for use in vibro ground improvement." *Proceedings of the Institution of Civil Engineers-Ground Improvement*, 6(2), 59-68.

Meran, C., Ozturk, O., and Yuksel, M. (2008). "Examination of the possibility of recycling and utilizing recycled polyethylene and polypropylene." *Materials & Design*, 29(3), 701-705.

Nataatmadja, A., and Tan, Y. (2001). "Resilient response of recycled concrete road aggregates." *Journal of Transportation Engineering*, 127(5), 450-453.

Paranavithana, S., and Mohajerani, A. (2006). "Effects of recycled concrete aggregates on properties of asphalt concrete." *Resources, Conservation and Recycling*, 48(1), 1-12.

Poon, C. S., and Chan, D. (2006). "Feasible use of recycled concrete aggregates and crushed clay brick as unbound road sub-base." *Construction and Building Materials*, 20(8), 578-585.

Puppala, A., Mohammad, L., and Allen, A. (1997). "Engineering behavior of lime-treated Louisiana subgrade soil." *Transportation Research Record: Journal of the Transportation Research Board*(1546), 24-31.

Puppala, A. J., Hoyos, L. R., and Potturi, A. K. (2011). "Resilient Moduli Response of Moderately Cement-Treated Reclaimed Asphalt Pavement Aggregates." *Journal of Materials in Civil Engineering*, 23(7), 990-998.

Rahman, M. A., Imteaz, M., Arulrajah, A., and Disfani, M. M. (2014). "Suitability of recycled construction and demolition aggregates as alternative pipe backfilling materials." *Journal of Cleaner Production*, 66, 75-84.

Schwartz, M. (2002). *Encyclopedia of materials, parts and finishes*, CRC Press.

Thach Nguyen, B., and Mohajerani, A. (2016). "Possible simplified method for the determination of the resilient modulus of unbound granular materials." *Road Materials and Pavement Design*, 1-18.

Thom, N. (2008). *Principle of Pavement Engineering*, Thomas Telford Publishing, London, UK.

Witczak, M., Kaloush, K., Pellinen, T., El-Basyouny, M., and Von Quintus, H. (2002). "NCHRP Report 465: Simple Performance Test for Superpave Mix Design." TRB, National Research Council, Washington, D. C.

Wong, S. L., Ngadi, N., Abdullah, T. A. T., and Inuwa, I. M. (2015). "Current state and future prospects of plastic waste as source of fuel: A review." *Renewable and Sustainable Energy Reviews*, 50, 1167-1180.

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Table 1. Physical properties of RCA, HDPE and LDPE.

Material	G_s	D_{max} (mm)	D_{50} (mm)	Particle shape	Sphericity of particle
RCA	2.69	19.00	3.99	Bulky	-
HDPE	0.94	4.75	3.51	Bulky	1.05
LDPE	0.92	6.30	4.04	Bulky	0.86

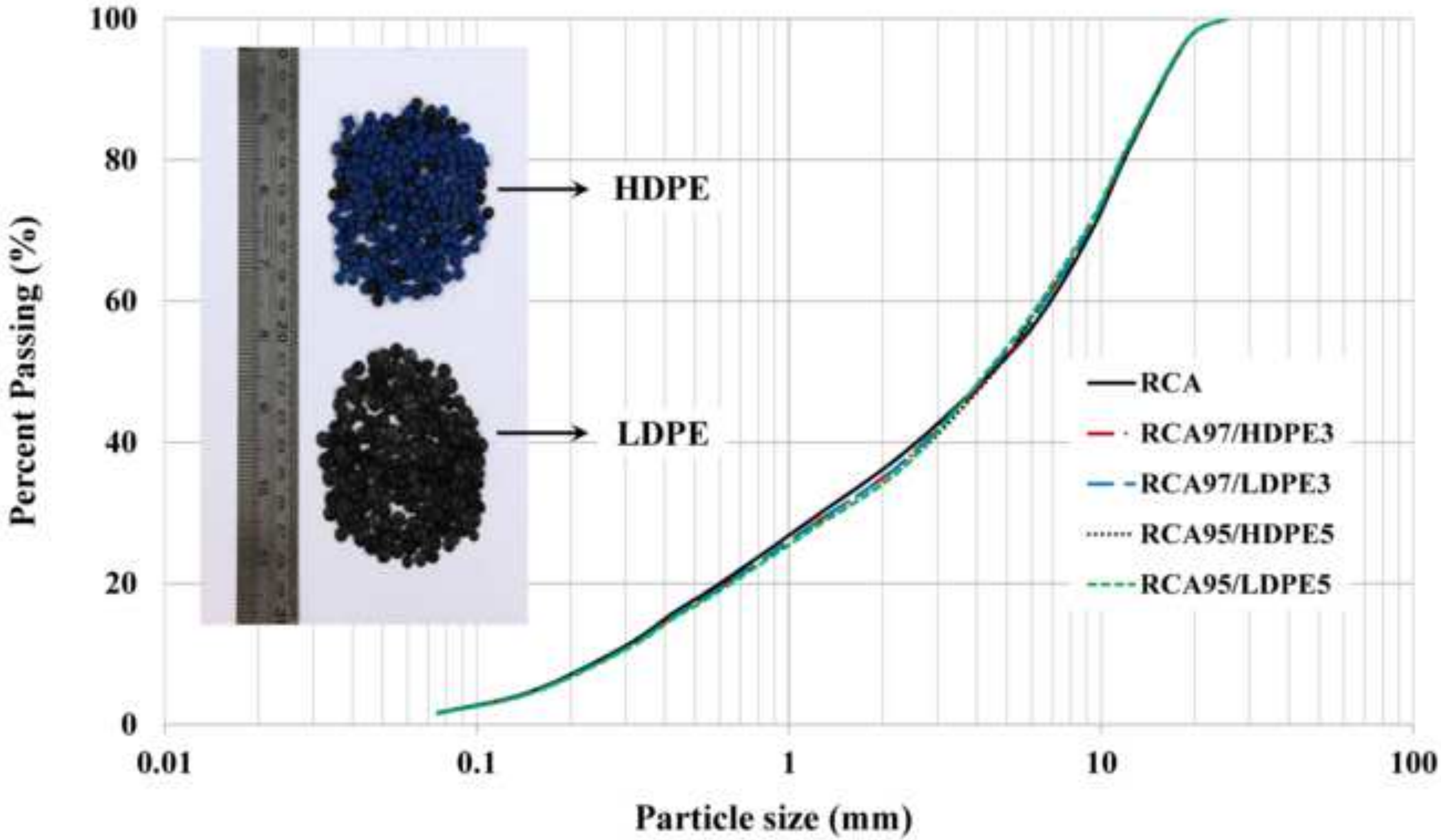
Table 2. Compaction and CBR test results on blends of RCA and RCA/plastic

Blend	MDD (Mg/m3)	OMC (%)	CBR @ 2.54 mm penetration	CBR @ 5.08 mm penetration
Pure RCA	1.951	11.0	140-145	169-184
RCA97/HDPE3	1.866	12.1	108-114	148-158
RCA97/LDPE3	1.836	11.7	91-99	118-131
RCA95/HDPE5	1.854	13.1	94-106	137-146
RCA95/LDPE5	1.825	12.7	90-95	119-126

Table 3. Stiffness properties of all blends

Blend	Pure RCA	RCA97/ HDPE3	RCA97/ LDPE3	RCA95/ HDPE5	RCA95/ LDPE5
Void ratio	0.39	0.41	0.43	0.42	0.41
E (MPa)	58.15	21.7	17.8	20.6	12.5
E_{50} (MPa)	50.43	18.6	11.9	17.3	9.8
ν	0.263	0.242	0.226	0.217	0.197

Figure 1



HDPE
LDPE
RCA
RCA97/HDPE3
RCA97/LDPE3
RCA95/HDPE5
RCA95/LDPE5
Percent Passing (%)
Particle size (mm)
0
20
40
60
80
100
0.01
0.1
1
10
100

Figure 2

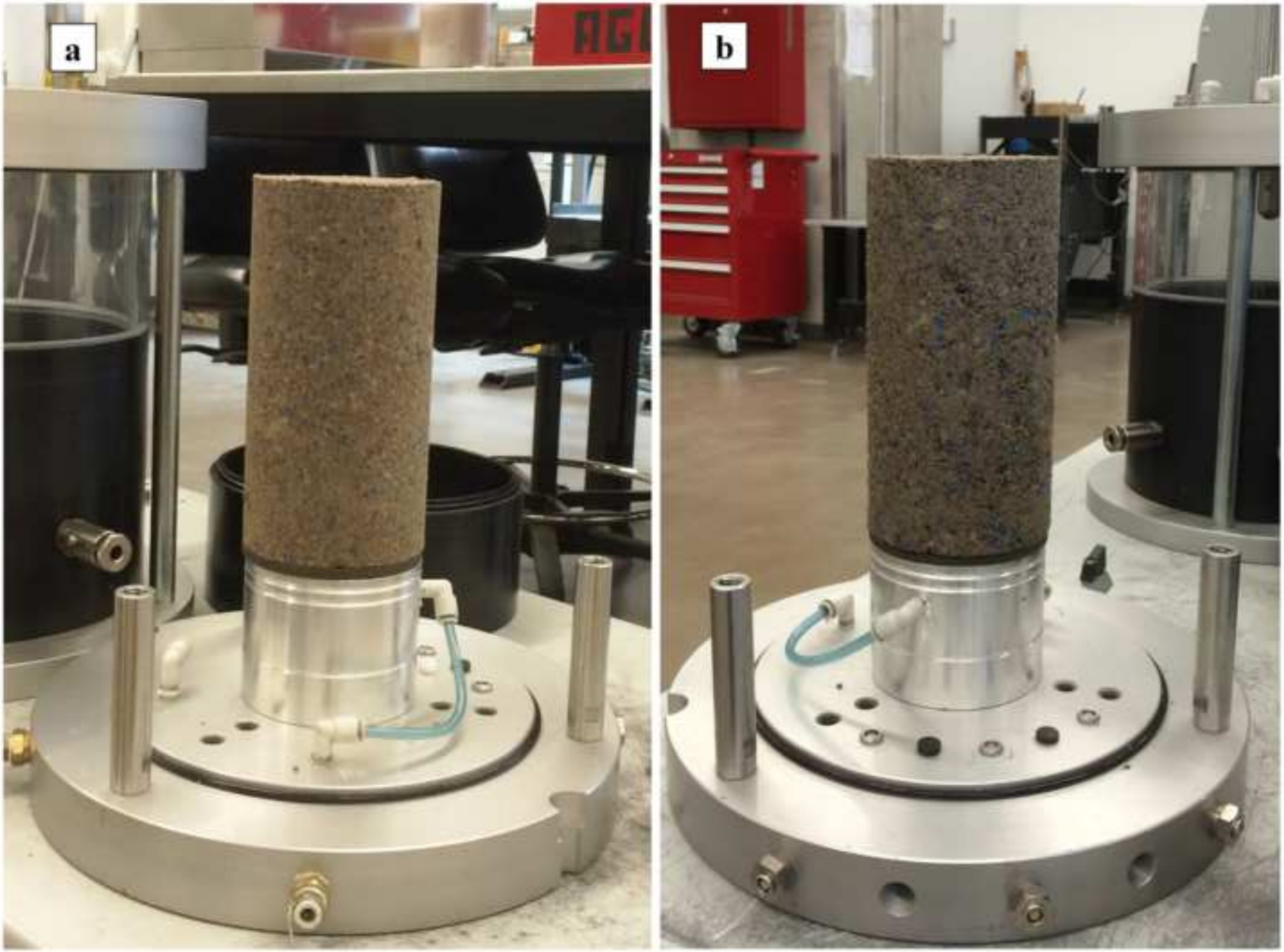
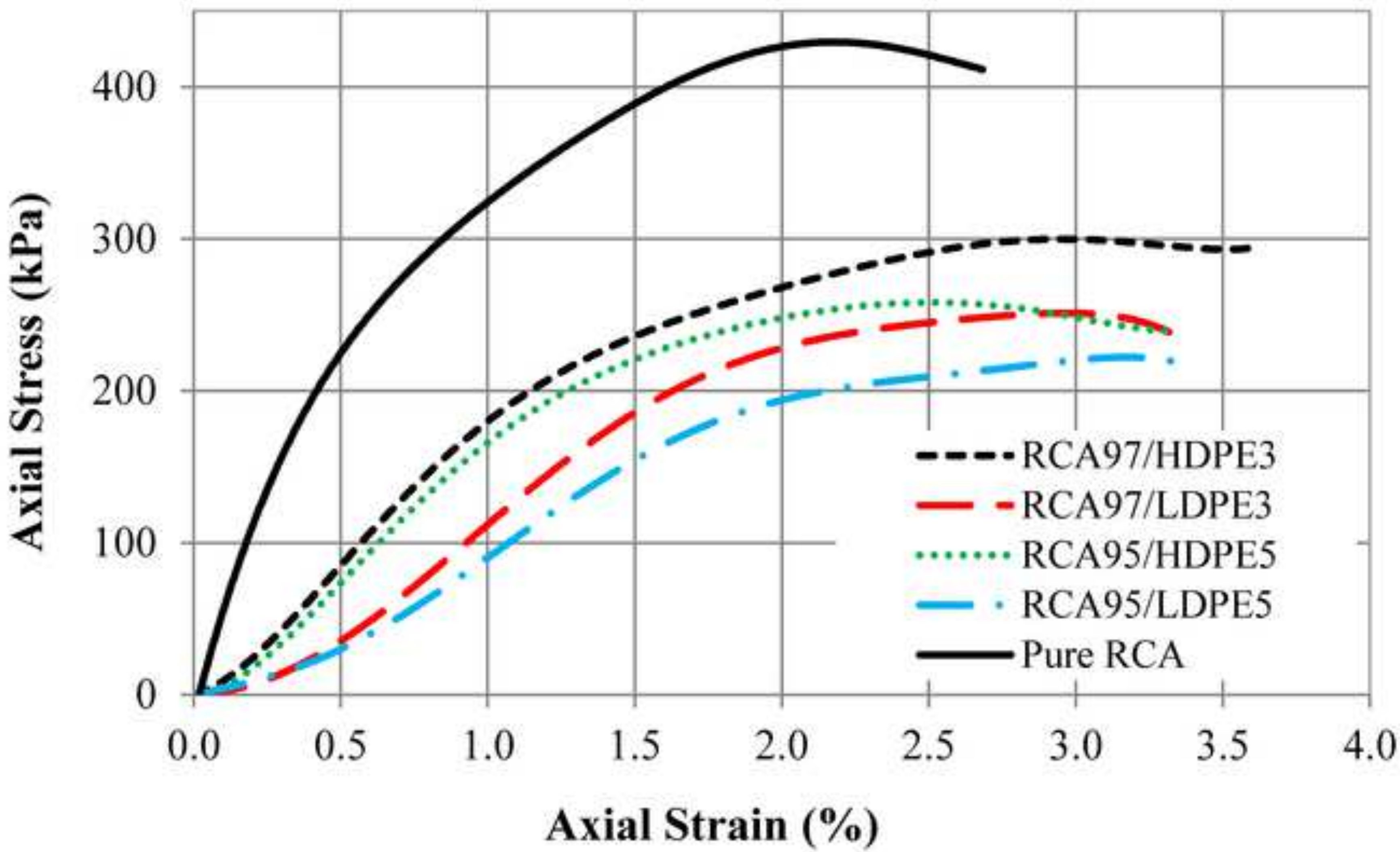
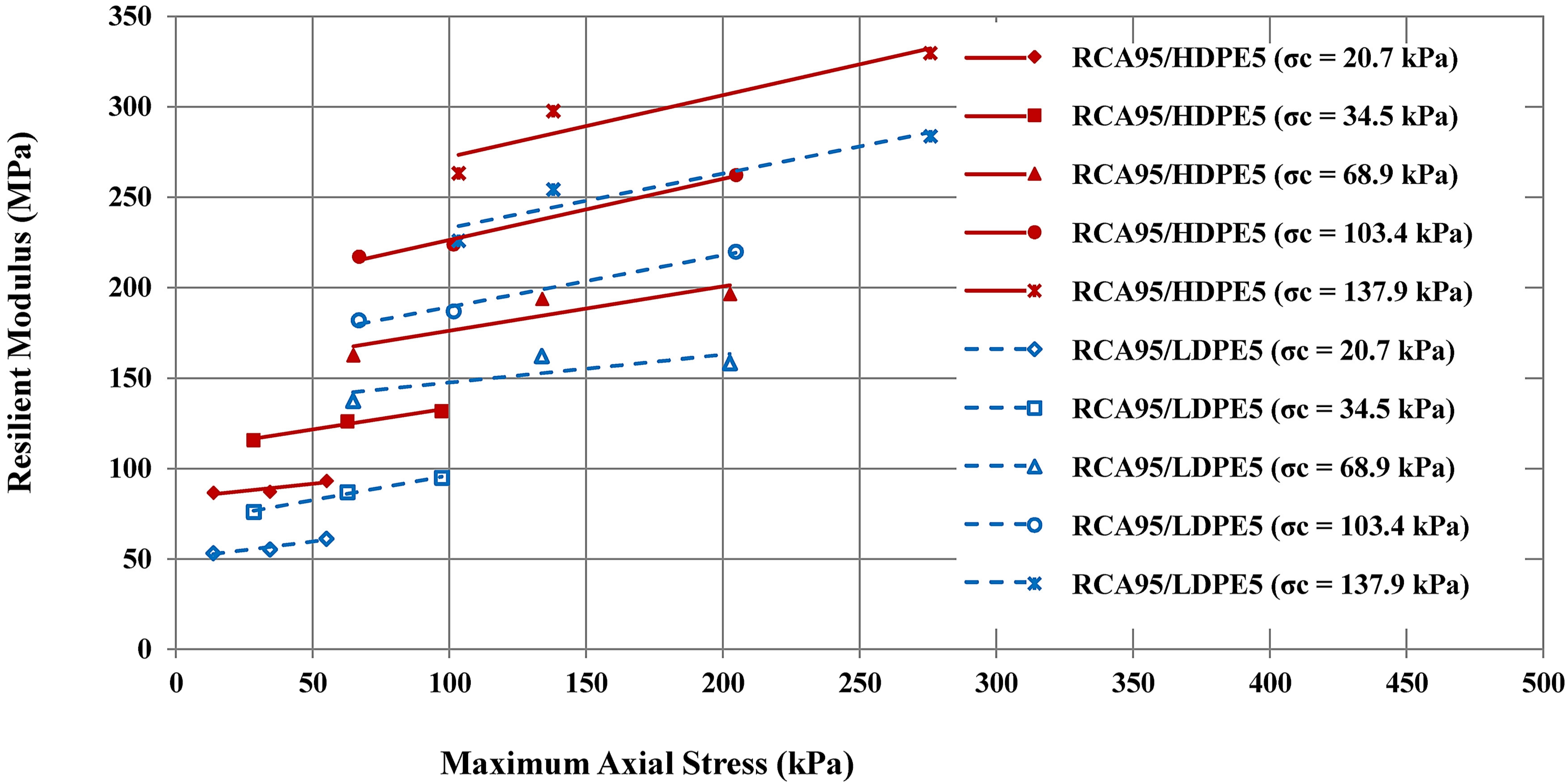


Figure 3

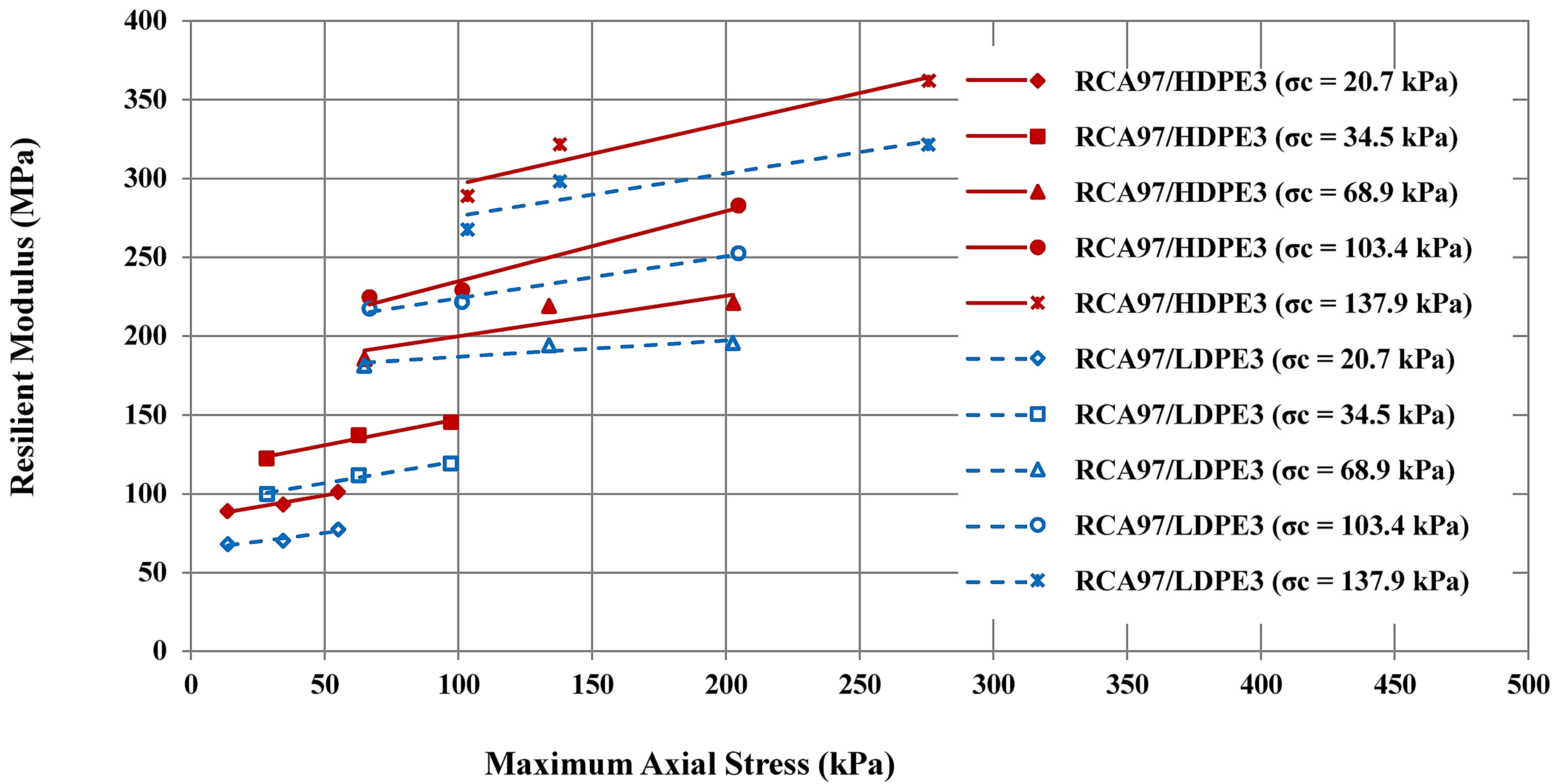


Axial Stress (kPa)
400
300
200
100
0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
Axial Strain (%)
RCA97/HDPE3
RCA97/LDPE3
RCA95/HDPE5
RCA95/LDPE5
Pure RCA



350
300
250
200
150
100
50
0
0
50
100
150
200
250
300
350
400
450
500
Resilient Modulus (MPa)
Maximum Axial Stress (kPa)
RCA95/HDPE5 (σc = 20.7 kPa)
RCA95/HDPE5 (σc = 34.5 kPa)
RCA95/HDPE5 (σc = 68.9 kPa)
RCA95/HDPE5 (σc = 103.4 kPa)
RCA95/HDPE5 (σc = 137.9 kPa)
RCA95/LDPE5 (σc = 20.7 kPa)
RCA95/LDPE5 (σc = 34.5 kPa)
RCA95/LDPE5 (σc = 68.9 kPa)
RCA95/LDPE5 (σc = 103.4 kPa)
RCA95/LDPE5 (σc = 137.9 kPa)

Figure 5



Resilient Modulus (MPa)
400
350
300
250
200
150
100
50
0
0
50
100
150
200
250
300
350
400
450
500
Maximum Axial Stress (kPa)
RCA97/HDPE3 (σc = 20.7 kPa)
RCA97/HDPE3 (σc = 34.5 kPa)
RCA97/HDPE3 (σc = 68.9 kPa)
RCA97/HDPE3 (σc = 103.4 kPa)
RCA97/HDPE3 (σc = 137.9 kPa)
RCA97/LDPE3 (σc = 20.7 kPa)
RCA97/LDPE3 (σc = 34.5 kPa)
RCA97/LDPE3 (σc = 68.9 kPa)
RCA97/LDPE3 (σc = 103.4 kPa)
RCA97/LDPE3 (σc = 137.9 kPa)

Figure 6

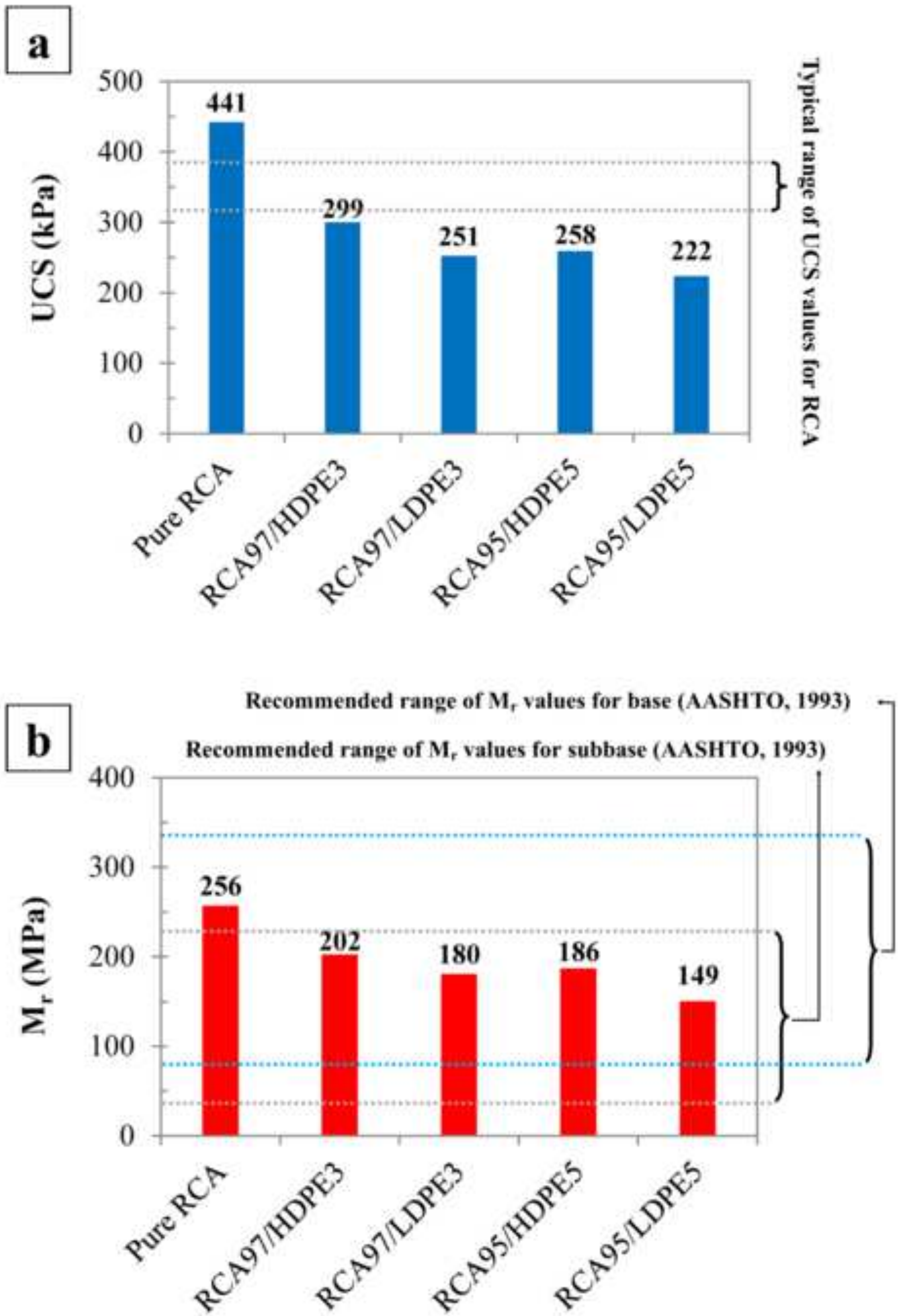

a
UCS (kPa)
500
400
300
200
100
0
441
299
251
258
222
Typical range of UCS values for RCA
Pure RCA
RCA97/HDPE3
RCA97/LDPE3
RCA95/HDPE5
RCA95/LDPE5
b
Recommended range of Mr values for base (AASHTO, 1993)
Recommended range of Mr values for subbase (AASHTO, 1993)
Mr (MPa)
400
300
200
100
0
256
202
180
186
149
Pure RCA
RCA97/HDPE3
RCA97/LDPE3
RCA95/HDPE5
RCA95/LDPE5

Figure 7

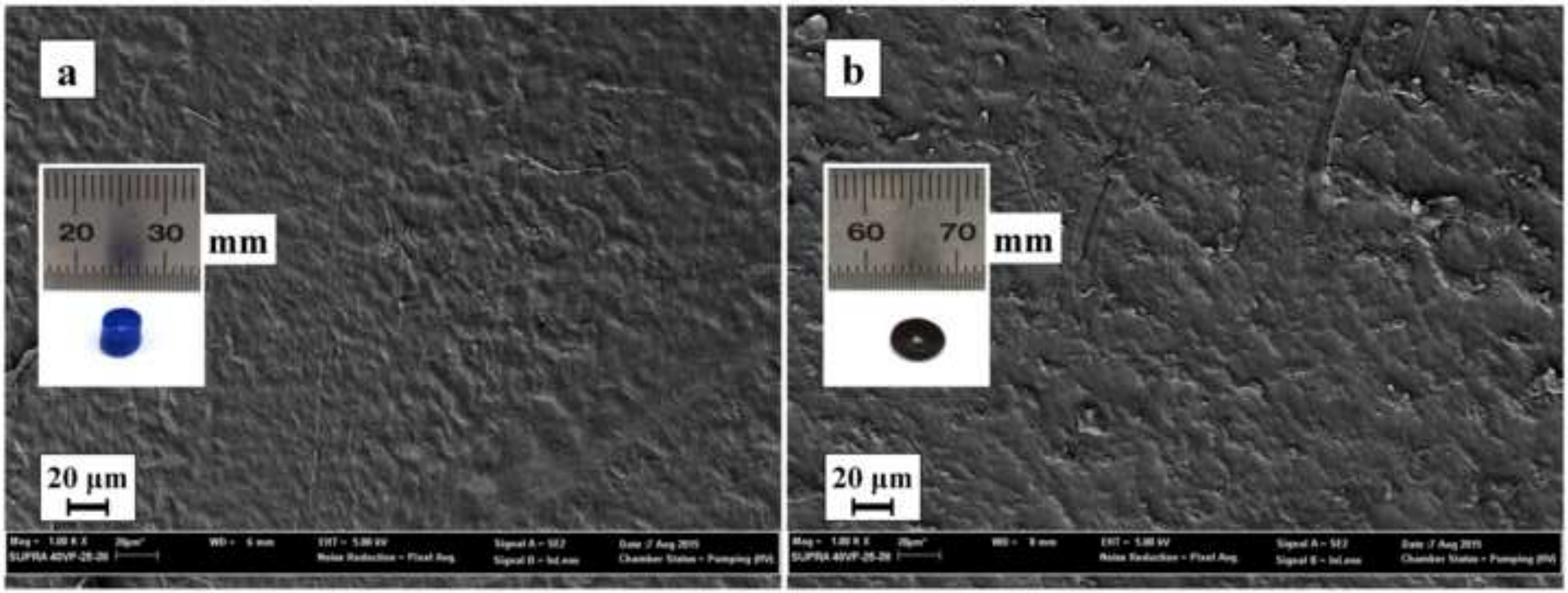


Figure 8

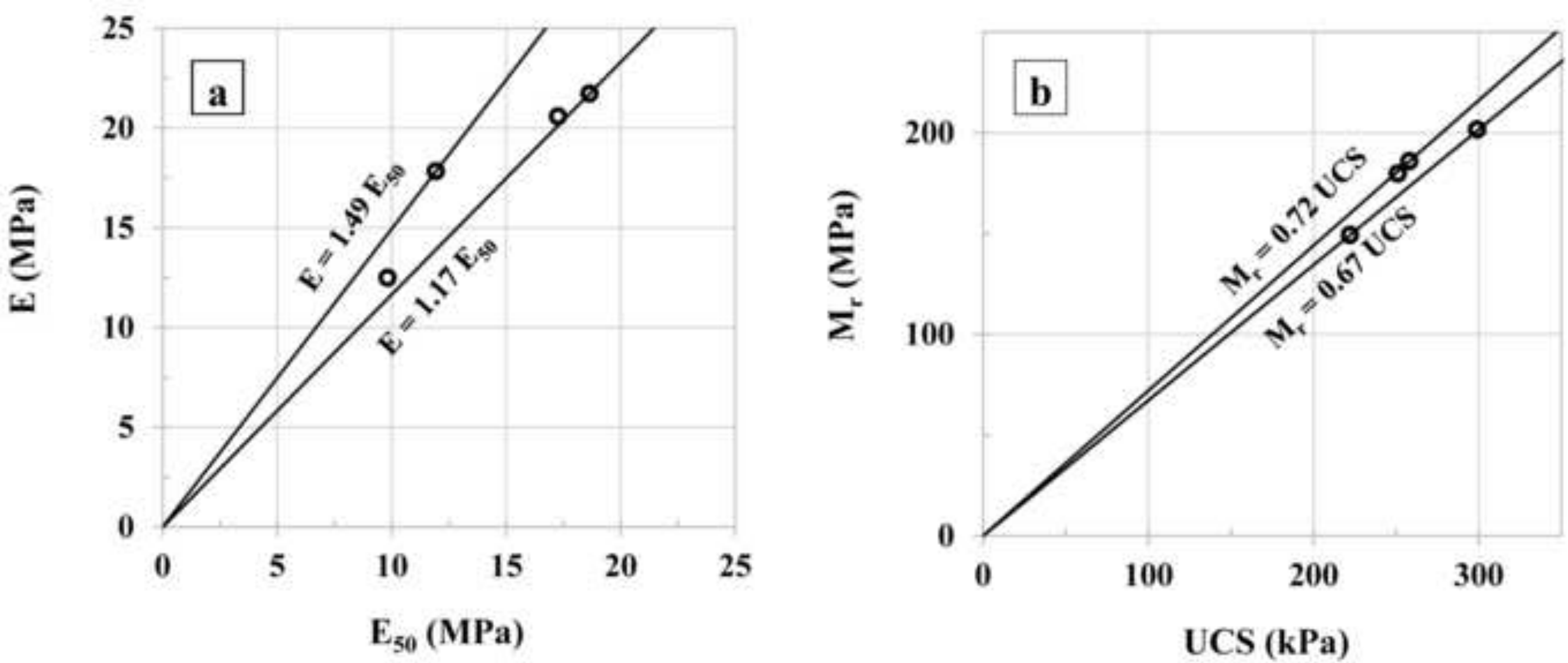
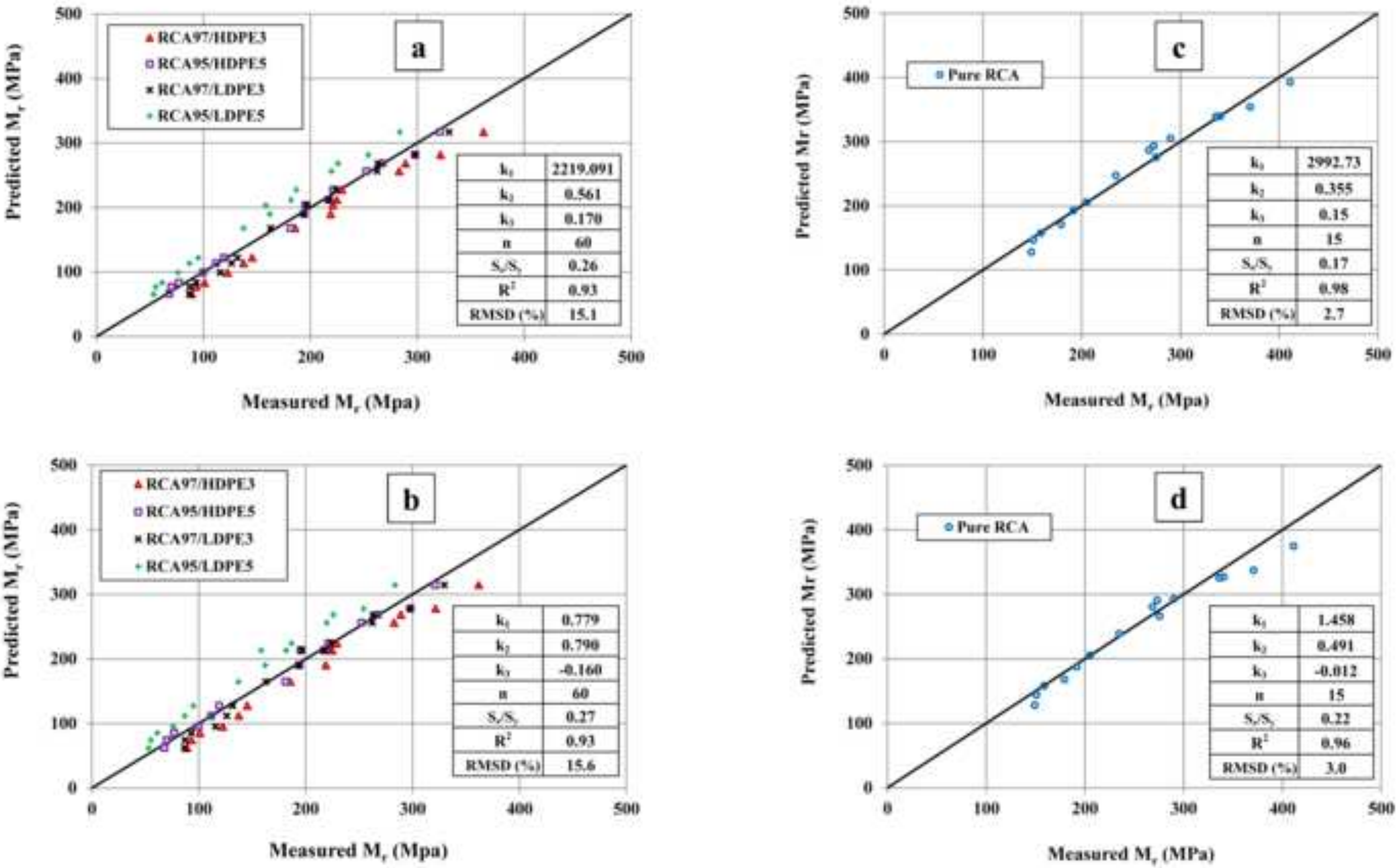

a
E = 1.49 E50
E = 1.17 E50
E (MPa)
E50 (MPa)
0
5
10
15
20
25
b
Mr = 0.72 UCS
Mr = 0.67 UCS
Mr (MPa)
UCS (kPa)
0
100
200
300

Figure 9


a
b
c
d
RCA97/HDPE3
RCA95/HDPE5
RCA97/LDPE3
RCA95/LDPE5
Pure RCA
Predicted M_r (MPa)
Predicted Mr (MPa)
Measured M_r (Mpa)
Measured M_r (MPa)
k_1 2219.091
k_2 0.561
k_3 0.170
n 60
S_e/S_y 0.26
R^2 0.93
RMSD (%) 15.1
k_1 0.779
k_2 0.790
k_3 -0.160
n 60
S_e/S_y 0.27
R^2 0.93
RMSD (%) 15.6
k_1 2992.73
k_2 0.355
k_3 0.15
n 15
S_e/S_y 0.17
R^2 0.98
RMSD (%) 2.7
k_1 1.458
k_2 0.491
k_3 -0.012
n 15
S_e/S_y 0.22
R^2 0.96
RMSD (%) 3.0