The Friction and Dilatancy Angle of Recycled Concrete Aggregate

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Abstract. Recycled Concrete Aggregate (RCA) is a construction and demolition material, which in unbound state can be placed as subbase in road structures. Over last decades there was many investigations which highlighted physical and mechanical properties of this material. Nevertheless, successful application of RCA still needs more tests. For sustainable development of road engineering, utilization of recycled material is essential. In this article direct shear tests were performed to characterize mechanical properties of RCA. Direct shear tests were conducted with and without modification by adding metal frames to shear cubic shaped box with length of side equal 250mm. Material used in this paper was RCA in gradation with lead to recognize it as sandy gravel. Tests were performed for various moisture content material compacted with to respect of normal energy in Proctor method. Tests shows differences between direct shear with and without metal frames. For RCA tested in standard test conditions friction angle differs between 32.4° to 65.1°. Modification of test equipment results in friction angle equal 38.7° to 41.5°. Both tests indicated impact of moisture conditions during compaction. In this study, dilation angle analysis was also performed. Dilation angle values were in range from 5° to 10°. Brittle nature of RCA results in low value of the dilatancy index.

1. Introduction
State Request of construction materials enhance need of exploring new ways of reuse waste deposits. Developing of economy in Poland induce in recent years deposits of construction and demolition (C&D) materials such as demolished brick and concrete. In the other way increasing of ecological awareness, lead to concentrate on recycle waste building materials to engineering constructions. In field of road engineering the C&D materials were used in roads, embankments, pipes bedding and backfilling [1].

This trend become global standard of treating crushed concrete and other construction materials. Norway experience in this field have been converted to 2004 to road construction guidelines norm. Four-year test program, was the background of this event and consist group of tests both field and laboratory conducted in E6 highway construction program with use of recycled concrete aggregate as a road subbase material [2].
The cement bound mixtures made with steel slag, ladle furnace slag, waste foundry sand, glass wastes and coal ash subjected to compression and indirect tensile tests, give satisfactory results from 7.56 MPa to 0.78 MPa respectively [3].

Rapid development of economy in China lead to increase of produced concrete debris. This situation lead Chinese researches to search ways of utilization this material, especially in road sub-base [4]. Intensive studies afford in 2007, to establish standards of reuse recycled concrete aggregates (RCA) [5].

Tests of mechanical behaviour of soil composed of different class RCA added were performed [6]. Direct Shear Tests (DST) were performed by [7, 8]. The dynamic characterization is important for non-cohesive soils, which contain fines [9] was also conducted for RCA [10]. Results of the tests have shown that among six tested C&D materials, all meet the requirements of shear strength property for aggregates in road including RCA. Cyclic loading tests [11] and adding of sand to RCA samples were also performed [12]. Typical for road laboratory tests, including CBR [13], compaction, crushing susceptibility, freeze thaw and triaxle tests were also conducted [2]. Practical applications were studied by testing of the performance of road composed of RCA [14, 15]. Tests considers optimum moisture content and CBR test where RCA has lover CBR ratio as a Unbound Granular Materials (UGM) and higher optimum moisture content in respect to lower dry density when compared to natural aggregates. Among various possibilities of application, build into embankments is promised ways of apply RCA in road engineering. Application to such structures as embankments cause the need of basic mechanical properties such as friction angle and cohesion estimation. Therefore, tests, which lead to fast and uncomplicated obtaining these parameters in desired. By using the DST apparatus those parameters can be relatively easy to find. The DST method was proven to be proper test for road unbound granular materials in previous studies [7, 16].

DST is a proper method for mechanical parameters estimation in case of coarse aggregates. Unfortunately, the DST is also subjected to some inaccuracies in case of non-cohesive soils. Recent reports from DST studies on non-cohesive soils finds that, during shearing grains around the shear surface are subjected to this process. Reasonable active shear band, which is commonly related to the mean grain size \( d_{50} \) was suggested as a suitable characteristic element of shear box length. Shear band therefore can range from 8\( d_{50} \) to 20\( d_{50} \) [17]. Shear deformation studies on medium-sized sands were conducted in aim at developing an improved fundamental understanding of granular-continuum, stress-strain behaviour. Results demonstrated that evolution and progression of shear zone is affected by change of interface surface roughness and particle angularity. Inside the shear zone, soil dilation occurring in contact with the material counterface and soil contraction in a surrounding outer zone [18].

Discrete Element Method analysis has shown that during DST, the deformations and the stresses are strongly non-affine. Characteristic for shear zone shape and thickness appearing along a horizontal mid-section are non-uniform. Shape of the shear zone is the widest in mid-section and the shear zone behave periodically organised structure due to void ratio and vortex structures fluctuation [19].

Studies on active shear phenomena by base on Cosserat continuum extension of a hypoplastic model for granular media reveals the size effect near boundaries in shear deformation and thickness of shear band in failure. These phenomena quantity are proportional to the micro-structure length (the mean grain diameter). Abovementioned characteristics are dependent from micro-stiffness parameter and micro-strength parameter respectively. The results of calculations show a connection between size effects, the micro-structure length and material properties [20].

DST results show that gap space and specimen size had significant effects on shear strength. this effect is larger under a large normal stress than under smaller normal stress. Reported reasonable gap \( T \) is 0.86\( d_{\text{max}} \) \( \leq \) \( T \) \( \leq \) 1.28 \( d_{\text{max}} \) for soil sample with grain sizes 2-5mm and 1.0\( d_{\text{max}} \) \( \leq \) \( T \) \( \leq \) 1.3 \( d_{\text{max}} \) for soil sample with grain sizes 5-10mm, with height \( H \geq 10d_{\text{max}} \) [21].

Relative length to height of shear box was tested and confining stress to shear stress was analysed. For cubic shaped shear box shear stress to confining stress coefficient reach highest value and was equal near to 1. In small box stress distribution occurs across all grains and bigger part of soil mass is
involved in shear process. With increasing the shear box size stress distribution decompose on grains placed near to shear box walls [22]. Size of shear box have also impact on results of friction angle calculation [23]. In 1997, friction angle estimations for RCA in direct shear test were conducted. Studies performed in high volume shear box, presents various spectrum of friction angle value. After application of dilatancy index $I_d$ introduced by Bolton in [24], internal friction angle and natural angle of slip was controlled and results of this test lead to conclude that this discrepancies, eliminates this method as reference test [25].

C&D materials as RCA was studied in by using DST method where shear strength properties of geogrid-reinforced C&D aggregates were tested. Conducted comparison of interface shear strength properties between conventional and modified DST method revealed existence of apparent cohesion $c$ equal to 95kPa and friction angle $\phi$ equal to 65° [26]. A large DST for RCA with grain size 0-11mm shows apparent cohesion equal to 66.4kPa and friction angle $\phi$ equal to 52.1° [27].

Results from DST when the Mohr-Coulomb model is applied do not represent a point on the Mohr circle of stress which is tangent to the Mohr-Coulomb failure surface [28]. Parameters obtained from DST must be converted to plain strain parameters by using of the linking equations where dilation angle is required.

2. Materials and methods

2.1. Material and sample preparation

Material used in this study, was demolished concrete from building demolition site. Concrete aggregates were an element of concrete walls and floor which strength class estimated from C16/20 to C30/35. Aggregates composed from broken cement concrete in 99%, the rest consists of glass and brick ($\Sigma(R_b, R_g, X)\leq 1\%\text{ m/m}$) and contains no asphalt or tar elements. Grain gradation curve was adopted in respect to polish technical standard [29] and placed between upper and lower grain gradation limits.

2.2. Physical properties analysis

For estimation of physical properties, series of tests were conducted. The material was sieved to appropriate gradations and later mixed to basic gradation curve. Sieve analysis was conducted under existing European standards [29]. The standard compaction tests were undertaken to determine the maximum dry density and optimum moisture content of the RCA material.

2.3. Basic mechanical properties analysis

The laboratory analysis was conducted to determine the engineering properties of RCA, included California Bearing Ratio (CBR) [30], cyclic CBR (cCBR). CBR tests were prepared from large samples of RCA, with respect to standard Proctor's method where preliminary tests highlighted the maximum dry density and optimum moisture content. The CBR tests were performed under existing standards. The RCA was studied by this method three times for each moisture content equal to 2.04%, 8.67% and 12.06%. The cCBR tests were conducted on sample prepared in CBR mould by applying the cCBR test procedure. The idea behind cCBR test comes from CBR test popularity, and uncomplicated procedure of test. The first step of cCBR test is standard CBR test loading to 2.54mm. When desired plunger penetration is reached, the unloading phase is performed to stress equal to 10% of maximal stress noted on 2.54mm penetration. The loading and unloading phases constitute first load cycle. The next cycles are performed to maximal and minimal stress obtained in first cycle. The test is carried out with 1.27mm/min velocity. The amount of cycles is determined by percentage of plastic displacement in one cycle. When in one cycle less than 1% of noted displacement is plastic, the test can be terminated.
2.4. Direct shear test procedure

The direct shear tests were conducted in a large shear box with cubic shape and length of side equal to 250 mm. Shear box was divided into two boxes, stationary bottom and moveable top. Fully self-contained hydraulic pressure cylinders generated normal and shear force with changeable box speed ranging from 0.01 mm/min to 1.0 mm/min. For tested RCA velocity was equal 0.01 mm/min to avoid possible missing of peak stress. Tests were performed with two series, standard and modified shear box. Modification of shear box is to adding metal frames with 0.005 m thickness between top and bottom boxes, which change direct shear surface. The compaction was conducted for material with moisture content close to 2, 8 and 12%. The detailed moisture content estimated after DST presents Table 1. The RCA was compacted in shear box with respect to Proctor's standard method (0.59 J·cm⁻³ compaction energy). The normal stress was loaded on top cap of shear box and the tests were conducted after vertical displacements reach constant value. On the top of metal cap, linear variable differential transformer (LVDT) was installed. When the LVDT records shows no further changes in sample high, the DST was performed. The DST were terminated once the horizontal shear strain reach 9% or visible peak and residual shear strength was recorded.

Table 1. Test conditions for RCA direct shear tests

| Test | Moisture (%) | \( \sigma \) (kPa) | \( \rho_d \) (g·cm⁻³) | \( I_d \) (%) | CBR (%) | \( M_r \) (MPa) |
|------|--------------|-------------------|---------------------|---------|-------|-------------|
| S1   | 2.2          | 19.52             | 1.887               | 0.669   | –     | –           |
| S2   | 2.04         | 29.76             | 1.883               | 0.665   | 58    | –           |
| S3   | 2.18         | 98.08             | 1.885               | 0.667   | –     | –           |
| S4   | 8.52         | 95.84             | 1.965               | 0.735   | –     | –           |
| S5   | 8.67         | 219.63            | 1.971               | 0.74    | 89    | 514.4       |
| S6   | 8.39         | 303.2             | 1.962               | 0.733   | –     | –           |
| S7   | 12.06        | 100.96            | 1.952               | 0.725   | 83    | –           |
| S8   | 11.99        | 223.52            | 1.952               | 0.725   | –     | –           |
| S9   | 12.22        | 324.32            | 1.949               | 0.722   | –     | –           |
| M1   | 2.18         | 49.76             | 1.885               | 0.667   | –     | –           |
| M2   | 2.05         | 69.12             | 1.883               | 0.665   | 58    | –           |
| M3   | 2.18         | 84.00             | 1.885               | 0.667   | –     | –           |
| M4   | 8.52         | 49.76             | 1.965               | 0.735   | –     | –           |
| M5   | 8.7          | 70.24             | 1.97                | 0.74    | 89    | 514.4       |
| M6   | 8.39         | 83.52             | 1.962               | 0.733   | –     | –           |
| M7   | 12.06        | 51.2              | 1.952               | 0.725   | 83    | –           |
| M8   | 11.99        | 71.36             | 1.952               | 0.725   | –     | –           |
| M9   | 12.22        | 86.08             | 1.949               | 0.722   | –     | –           |

3. Results and discussion

3.1. Physical properties results

The sieve analysis lead to classification of material as sandy gravel (saGr), in refer to [29]. Test results are shown in Figure 1. This distribution of particles from 31.5 mm to 0 mm is the standard for soils used for sub-base and support structures. The coefficient of uniformity (Cu) and coefficient of curvature (Cc) was calculated. For tested material Cu was equal to 54.5 and Cc was equal to 1.5 which is stated for well graded material [29]. Results of the Proctor test presents Figure 1. The test was conducted by compaction in the Proctor mold, which volume equalled 2.2 dm³, by using standard energy of compaction, equal to 0.59 J·cm⁻³. Optimum moisture content for sandy gravel was \( m_{opt} = 8.67\% \) and maximum dry density of optimum moisture content was 1.97 g/cm³. After the optimum moisture content estimation and the peak dry density \( \rho_{ds} \) for tested samples relative density calculation
was performed. Table 1 presents the test conditions for RCA samples in direct shear test. The S index represent standard DST procedure, the M index corresponds to modified DST.

![Figure 1](image1.png)

**Figure 1.** Physical properties of RCA: (a) particle size distribution of tested soil (b) the Proctor test results for RCA.

### 3.2. CBR and cCBR test results
Before the DST, the standard CBR tests were conducted. The CBR tests results for RCA with 2.04%, 8.67% and 12.04% moisture content the CBR value was 58%, 89%, and 83% respectively. The resilient modulus $M_r$ value from cCBR test based on method presented by [13, 31] was equal to 514.4MPa for optimal moisture content. Figure 2 presents the basic mechanical properties results.

### 3.3. DST results
The results of the DS tests are presented on Figures 2 to 5. For three levels of moisture, 2%, 8% and 12% series of tests with and without metal frame modification were conducted. Data are presented in plots of shear stress to shear strain. For better presentation of this results plot of shear stress - vertical stress quotient ratio to shear strain were presented. Important result of data analysis are characteristic rules of direct shear tests for metal frames addition. On Figures 2 and 3 stress ratios are unified and these phenomena occur between 5% and 6% of shear strain and stress ratio oscillates 0.8. In contrast, direct shear test without modification results in various values of stress ratio (see Figure 2).

In case of samples with moisture content oscillating between 2%, the stress ratio were the highest during standard DST. This occurrence may be caused by high rigidity of dry grains and therefore higher friction between particles. Applying of the metal frames reduced this effect by letting the grains to roll over, to which could be observed on Figure 4. For 8% and 12% level, moisture content the vertical strain in standard test result is lower than for modified test results. The reason of that is change of friction between particles as a retaining force to shear stress, to grain rotation where stress needed for this phenomenon is lower than stress needed to shear friction between the grains.

The modified equipment results with more unified behaviour during the test than standard test. Samples behave slightly dilative in tests with metal frames modifications and in a few cases cross 1.0% of vertical strain. Standard tests behave dilative and compacting (S3 sample). Vertical strains were sharper and dilation of gravel fraction can be recognized on plots by characteristic rapid changes in the stress-strain characteristics (e.g. Figure 4, S5, S6 sample) and sound effects during test.
Figure 2. Results of DST for standard and modified direct shear apparatus in various moisture content and vertical stress values.

The ratio of shear stress to vertical stress (Figure 3 and 4) presents impact of metal frames on test results. In standard DST the ratio cross 1 in case of dry samples. Modified DST is uniform and the ratio do not cross 1. In modified DST, characteristic peak was not observed. Standard DST samples S7, S8, S9 also have not present this phenomenon. This may be caused by high friction between grains. RCA have high internal porosity [32] and therefore water, which moistens the grains not entirely coats surface of the grain. Modified DST also shows mechanism of shearing in RCA. When shear plane in standard DST presented as surface, important role in this phenomena lays in friction between the grains and strength of the grains. In modified DST when shearing forces acting on volume, rotation of the grains is mobilised first during shearing. Skewing of the grains between themselves caused grain crushing which can be observed as a characteristic sound and which occurs in standard DST.
Figure 3. Plot of vertical strain to shear strain from direct shear tests for samples with and without modification of shear box.

Results of direct shear test with modification represent more steady and uniform course. The conclusion can be drawn the dilative or compacting behaviour of tested material were utilized between metal frames. This is more suitable to natural behaviour of RCA during shearing. Figure 4 presents results of calculation friction angle for tested material. Analysing of standard test results led to two conclusions, firstly, range of friction angle varied from 32.4° to 65.1° what indicates tremendous impact of moisture on friction angle in plane shear conditions. Second remark concerns homogeneity of shear test results. For the same moisture estimated equation have lower coefficient of determination R² value (0.97 to 0.98) than for modified test results (R² = 0.99). Modified direct shear tests results with friction angle varying from 38.7° to 41.5°. In comparing these two kinds of tests, modified shear test seems to presents more uniform data. To confront obtained results with another simple test, loose heap test were conducted. Result of tests in tube with 25.4 cm diameter, give friction angle equal to 40°. Tests were conducted in full saturated conditions. Friction angle obtain from loose heap test is similar to 8% moisture content friction angle. This may indicated slightly impact of moisture on grain performance on friction properties.
Figure 4. Plot of shear stress to normal stress from direct shear tests for samples with and without modification of shear box.

4. Conclusions
In this paper results of DST on recycled concrete aggregate was presented. Carried tests on direct shear apparatus consist in the standard procedure of test and the modified procedure, which contained modification of the shear box. The metal frames were added between shear zone and extend shear area. Paper result in some conclusions:

- Modified direct shear apparatus give more unified data and results of tests in different moisture content and confining pressure were more alike in comparison to standard tests. The reason for that is grain rotation during shearing in modified DST. In standard DST, the rotation is not possible because of skewing of the grains and therefore shearing in governed by grain crushing and friction.
- Dilatancy behaviour in modified procedure of DST were more steady and homogenous than standard direct shear. The modified DST results present more natural for the RCA failure mechanism. The RCA during shearing dilates and failure is caused by the grain movement. The phenomena of grain movement may come from relatively high, in compare to natural aggregates, friction forces between RCA grains. This friction mobilises itself as grain movement where the grains cannot slip but rotates between themselves.
- It is possible that maximal stress ratio occurs between metal frames when in case of standard DST maximal stress ratio plane could appear not in direct shear zone. The standard DST lead to the grain skewing. The shear zone occurs in fixed place and the movement of the grains trigger more dilative behaviour.
- For the RCA form standard DST the friction angle varied from 32.4° to 65.1°. Modified DST results shows friction angle varying from 38.7° to 41.5°. Results from standard DST may suggest also the existence of apparent cohesion of this material. Modified DST clearly shows that there is no extra apparent cohesion.
- The brittle nature of RCA, its grain angularity and moisture characteristics lead to another behaviour of this material during shearing. Therefore, the modified DST are better test for friction angle estimation for such material.

The aforementioned results suggest a possibility to recycle RCA as a UGM for, e.g. subbases. Test results concerning lack of moisture and nearly soaked conditions were mixed. Those circumstances are negative and mostly affect the performance of subgrade constructed from RCA. CBR tests show a drop of bearing capacity in case of low moisture content and slightly lower CBR results for high moisture content. The RCA in optimum moisture content reached the CBR value exceeding 89%, DST
friction angle from modified test equal to 37° and resilient modulus from cCBR test equal to 514.4MPa. The moisture content did not affect friction angle when modified DST results are analysed. On the other hand, low moisture content RCA samples did not cross 58% of CBR value. Upon comparing the impact of the previously mentioned properties on bearing capacity saturation conditions, the RCA is more sensitive to low moisture content when bearing capacity is analysed.

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