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Strength of Individual Soil Aggregates Against Crushing Forces I. Influence of Aggregate Characteristics

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Abstract: This study was undertaken to determine the relative strength of individual soil aggregates of different sizes and shapes against crushing forces. Soil aggregates were placed individually between a clean–fixed flat surface and a flat plate connected to a pocketpenetrometer and crushed under applied stress. The results of this study show that the strength of the aggregates against disruptive forces was directly related to aggregate size and shape. As the aggregate size increased, so did the applied stress required to crush the aggregate. Significant relationships were found between applied stress and the mass, volume, average diameter (D_{avg}) and geometric mean diameter (D_{gm}) of the aggregates.

Bireysel Toprak Agregatlarının Kırılmaya Karşı Dayanıklılıkları I. Aggregat Özelliklerinin Etkisi

Özet: Bu çalışma, farklı büyüklük ve kütleye sahip bireysel toprak agregatlarının kırılmaya karşı olan dayanıklılıklarını belirlemek amacıyla yürütülmüştür. Agregatlar temiz ve pürüzsüz bir zemin ile buna paralel konumda ve cep penetrometresine sabitleştirilmiş iki plaka arasına yerleştirilmiş ve yavaş yavaş arttırılarak uygulanan basınç altında kırılmıştır. Araştırma sonuçları, toprak agregatların tahrip edici mekaniksel kuvvetlere karşı olan dayanıklılıklarının agregatların büyüklük ve şekilleri ile doğrudan ilişkili olduğunu göstermiştir. Agregat büyüklüğü arttıkça, kırılması için uygulaması gereken basınç da artmıştır. Uygulanan basınç değerleri ile agregatların kütlesi, hacmi, ortalama çapı (D_{avg}) ve geometrik ortalama çap (D_{gm}) değerleri arasında önemli ilişkiler kaydedilmiştir.

Introduction

Soil reaction to mechanical loads and applied disruptive forces is very important in the making of effective soil management decisions. One of the major components in soil degradation is the breaking up of soiL aggregates by agricultural machines and tillage implements. The permanence of aggregates depends on their ability to retain their shape after being subjected to disruptive effects of raindrops and tillage (1). Cropping sequences, crop management practices, fertility, drainage, irrigation and the quality of water that intreacts with soil aggregates all affect their size and strength (2).

The formation of soil structure requires both physical rearrangement of particles and the stabilization of the new arrangement. Aggregation results either from bridging between primary particles or as the result of the attraction of primary particles to each other. Stability is particularly associated with organic materials linking mineral particles together and with clay minerals and sesquioxides (3, 4). Therefore, the stability and response of soil aggregates to stress depend on the relative importance of different bonding mechanisms. The more strongly the particles in an aggregate are held together, the greater the work that has to be done to break the bonds (5).

Dry–soil aggregate stability is commoly used to evaluate soil properties in studies on tillage and wind erosion research (6, 7, 8, 9). Rogowski et at. (10) used an unconfined compression apparatus to break up individual aggregates assumed to have spherical shape and to determine the relationships between rupture parameters and other soil properties. They emphasized that since the field aggregates might be considered as the smallest stable units of soil mass, their size distribution and mechanical properties should largely determine the dynamic behavior of agricultural soils. Powers and Skidmore (11) defined dry aggregate stability as the energy needed to crush a compacted sample between two parallel plates. Perfect and Kay (12) compared the performance of specific rupture energy (E) and tensile strength (T) as statistical descriptors of dry aggregate strength. They reported that dry aggregate strength decreased with increasing size and decreasing tillage intensity.

Tensile strength, the most useful measure of the strength of individual soil aggregates, can be calculated from crushing forces if the aggregate diameters are known (13). In this test, aggregates are placed between parallel plates until aggregate failure occurs, and the aggregate tensile strength required to crush the aggregates is measured. In another test, Misra et. al. (14) determined the maximum penetrometer pressure on artificial soil aggregates of finite size using by blunt probes. They measured the penetration force using an electronic balance on which the aggregate was supported by means of three glass spheres.

Skidmore and Layton (15) crushed individual soil aggregates by loading them diametrically between parallel plates. They called the applied force at the time of fracture the "initial break force" and divided the work required to crush each aggregate by the mass of the aggregate being crushed to give a measure of aggregate stability (AS). They found a good relationship between AS and initial break force.

The objective of this study was to determine the relative strength of individual soil aggregates of different sizes and shapes against crushing forces.

Material and Methods

Surface soil samples (0–20 cm) collected from ten different locations were taken to the laboratory and air dried. The air–dried clod samples were sorted by sieving into four aggregate size groups: A–1: 25.4–19.05 mm (1–1/4 in); A–2: 19.05–9.53 mm (3/4–3/8 in); A–3: 9.53–4.76 mm (3/8–3/16 in); and A–4: 4.76–3.18 mm (3/16–3/24 in). The aggregates in each group were divided into two sub–groups. The first group of aggregates was crushed after their sizes and masses had been recorded. The second group of aggregates was oven–dried at 105°C for 24 h before crushing. The reason for using over–dry aggregates was to eliminate the effects of aggregate water content on crushing forces. Dexter and Kroesbergen (13) considered the oven–dry state a standard reproducible condition and they do not recommend measurement of air–dried aggregates since the small differences in aggregate water content can have a significant effect on tensile strength. After removal from the oven, the aggregates were allowed to cool in a desiccator containing dry P_2O_5. During the crushing test, the aggregates were removed individually from the desiccator, their sizes were measured using a compass and they were crushed according to the procedure described below.

Aggregates were placed individually on a clean–fixed flat surface in the most stable position and another flat plate connected to a pocket penetrometer was placed on the upper surface of the aggregate (Fig. 1). The penetrometer was pushed down steadily on the aggregate until aggregate failure occurred.

The test procedure used in our study was similar in many ways to the procedure described by Dexter and Kroesbergen (13) under the heading *"Crushing method for large and strong aggregates".* The main difference between the two procedures was that the load in their test apparatus was measured with a load ring (LR), whereas we evaluated the load as the number on the scale of the penetrometer at the time of aggregate failure and called the load as the applied stress, expressed in kg/cm^2. Since the pocket penetrometer is designed to determine penetration resistance and not to crush aggregates, the numerical values of applied stress given in this paper may not be suitable for comparison with the tensile strength of individual aggregates given by Dexter and Kroesbergen (13). Our main goal in using the pocket penetrometer was just to compare the relative strength of individual aggregates of different sizes and shapes against crushing forces.

Aggregate characteristics: the largest (D_l), intermediate (D_i), and smallest (D_s) diameters, the ratio of D_l/D_s, average aggregate diameter (D_{avg}), mean aggregate diameter (D_{mean}), geometric mean diameter

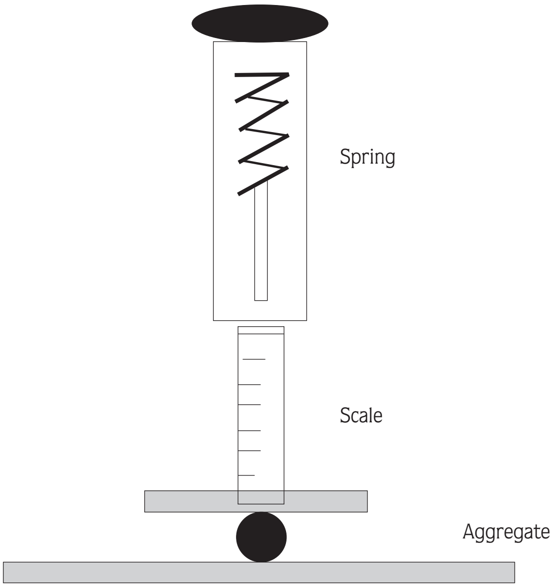

Figure 1. Adapted pocket penetrometer used to crush soil aggregates.

(D_{gm}), volume (V) and mass (M) were measured for each aggregate. D_l, D_i and D_s were measured using a compass. D_{avg} was calculated by dividing the sum of D_l, D_i and D_s by 3. D_{mean} and D_{gm} were found according to the method of Dexter and Kroesbergen (13). The shapes of the large aggregates, especially in the first two groups (A–1 and A–2), were mostly irregular. Therefore, the volume of each aggregate was obtained by multiplying three diameters instead of assuming that the shapes of the aggregates crushed were spherical.

The relationship between the aggregate characteristics mentioned above and the applied stress were evaluated using correlation and regression analysis (16).

Results and Discussion

Selected properties of the soils studied are described in the second paper of this series (17), which examines the influence of soil properties on the strength of individual soil aggregates against crushing forces. The soils tested contained 18 to 64% clay, 1.61 to 3.39% organic matter and 0.45 to 23.8% $CaCO_3$. Texturally, four soils out of 10 were clay (C), another four were loam (L) and the other two were clay loam (CL).

The relationship between mean aggregate diameter and applied stress is shown in Figure 2. It indicates that as the size of an aggregate increases, the applied stress required to break up the aggregate is greater. Each value on the graph represents an average of 4 to 30 measurements. Since similar linear relationships were found for all the soils, only one graph is presented here. The coefficient or determination (r^2) values for the relationship between D_{mean} and applied stress were between 0.861 and 0.991 for air–dry aggregates and 0.888 and 0.999 for oven–dry aggregates.

The shape of an aggregate is very important in crushing tests. Dexter and Kroesbergen (13) emphasized that a major source of variation in crushing force was due to the variability in aggregate shape. In general, researchers working on aggregate strength against crushing forces have assumed that the shape of aggregates is spherical (10). Misra et. al. (14) prepared artificial aggregates and agitated them in a closed container to round off the corners. However, in our study the aggregates were kept in their original shapes after passing through the sieve. The shapes of the aggregates were evaluated using the relationships between aggregate characteristics and applied stress. The results of the correlation analysis are summarized in Table 1. The aggregates in the A–1 size group are not included because of the limited number in each group. The aggregates in the A–4 size group are also excluded since we had difficulty in measuring their sizes by using a compass.

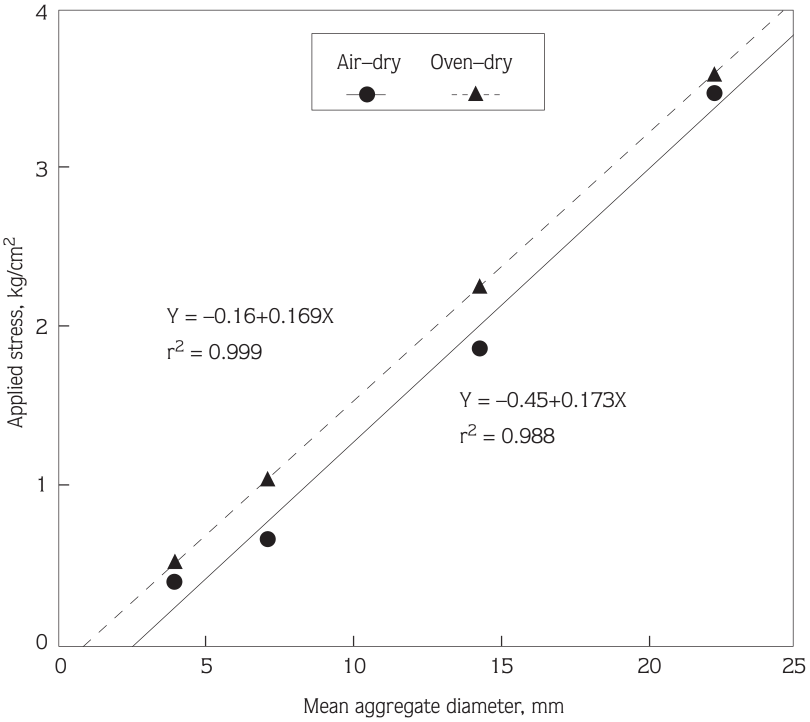

Figure 2. Relationships between mean aggregate diameter and applied stress.

In general, when r values were sorted from highest to lowest, the aggregate characteristics followed the same order as mass, D_{mean}, D_{gm}, volume, D_l, D_i, and D_s for both air and oven–dry aggregates in the A–2 size group. This indicates that the mass of an aggregate was the most significant aggregate characteristic in crushing the aggregates under applied stress. The volume of aggregates was also important in the crushing procedure. Therefore, it may not be a good approach to simply assume that the aggregate being tested has a spherical shape if aggregates are chosen randomly from an aggregate size group. When the aggregates are chosen randomly from an aggregate size group. When the aggregate diameter is considered, it can be said that both D_{mean} and D_{gm} are good indicators of crushing stress. D_l generally explained the highest variability in applied stress of the three diameters.

However, the order given above changed: mass, volume, D_{mean}, D_l, D_{gm}, D_i and D_s for air–dry aggregates and mass, Dgm, volume, D_{mean}, D_s, D_i and D_l for oven–dry aggregates and mass, D_{gm}, volume, D_{mean}, D_s, D_i and D_l for oven–dry aggregates in the A–3 size group. It was clear that mass, volume, D_{mean} and D_{gm} were the most important characteristics in the crushing procedure. There was no significant relationships between the ratio D_l/D_s and applied stress. Therefore, it is excluded from Table 1.

The number of aggregates crushed in each sub–group of four aggregate sizes was a minimum of 22, except for A–1 in which it ranged from 4 to 9 (Table 2). The aggregate diameters in each size group varied between the upper and lower limits given for the specified size groups. Therefore a representative set of small, intermediate and large aggregates was chosen from each group. In addition, the applied stress values required to crush an individual aggregate divided by the mass of the aggregate was called dry–aggregate stability, measured as kg/cm^2–g.

As shown in Figure 3, the dry–aggregate stability decreased with increasing mean aggregate diameter. This indicates that small aggregates were more stable than large aggregates against applied mechanical forces. Since the stability of aggregates is a function of whether the

Table 1. Correlation coefficients for relationships between applied stress and aggregate characteristics.

Soils	Air–dry aggregates							Oven–dry aggregates						
	Dl	Di	Ds	Davg	Dgm	Vol.	Mass	Dl	Di	Ds	Davg	Dgm	Vol.	Mass
	Aggregate Size: 19.05–9.53 mm													
Köprüköy Series	0.71**	0.52**	NS	0.68**	0.62**	0.68**	0.81**	0.75**	0.71**	0.54**	0.78**	0.76**	0.74**	0.78**
Uzunahmet Series	0.51**	0.56**	0.39*	0.54**	0.53**	0.51**	0.64**	0.51**	0.59**	0.45*	0.56**	0.56**	0.41*	0.58**
İspiryolu Series	0.80**	0.72**	0.84**	0.89**	0.89**	0.87**	0.88**	0.69**	0.71**	0.76**	0.82**	0.83**	0.85**	0.84**
Alaca series	NS	NS	NS	NS	NS	Ns	0.91**	0.76**	0.68**	0.65**	0.78**	0.77**	0.75**	0.79**
University–1	0.48**	0.61**	0.37*	0.63**	0.63**	0.66**	0.73**	0.65**	0.76**	0.46*	0.77**	0.76**	0.74**	0.72**
University–2	0.79**	0.71**	0.69**	0.84**	0.84**	0.82**	0.86**	0.63**	0.64**	0.49**	0.69**	0.68**	0.67**	0.79**
University–3	0.65**	0.73**	0.75**	0.77**	0.78**	0.78**	0.81**	0.66**	0.41*	NS	0.55**	0.51**	0.57**	0.67**
University–4	0.41*	NS	0.35*	0.43*	0.43*	0.39*	0.42*	0.64**	0.67**	0.61**	0.73**	0.73**	0.74**	0.78**
University–5	0.52**	0.49**	NS	0.62**	0.62**	0.61**	0.65**	NS	NS	NS	0.38*	0.41*	0.43*	0.43*
University–6	0.78**	0.61**	NS	0.78**	0.71**	0.73**	0.74**	0.82**	0.67**	0.37*	0.78**	0.73**	0.71**	0.79**
	Aggregate Size: 9.53–4.76 mm													
Köprüköy Series	NS	NS	NS	NS	NS	NS	0.44*	0.38	NS	NS	NS	NS	NS	0.66**
Uzunahmet Series	0.56**	0.63**	0.45*	0.65**	0.65**	0.66**	0.69**	0.53**	0.55**	0.74**	0.72**	0.75**	0.75**	0.84**
İspiryolu Series	0.49**	NS	NS	0.43*	NS	0.47**	0.92**	NS	0.48**	0.67**	0.49**	0.63**	0.59**	0.75**
Alaca Series	NS	NS	0.46*	0.38*	0.41*	0.42*	0.56**	NS	NS	NS	NS	NS	NS	0.54**
University–1	0.55**	NS	NS	NS	NS	0.36*	0.66**	NS	0.54**	0.56**	0.49**	0.53**	0.51**	0.71**
Univirsety–2	0.68**	0.72**	NS	0.56**	0.56**	0.57**	0.89**	0.64**	0.69**	0.68**	0.78**	0.81**	0.79**	0.87**
University–3	0.41*	0.43*	NS	0.48**	0.49**	0.43*	0.79**	0.68**	0.65**	0.56**	0.82**	0.81**	0.81**	0.85**
University–4	0.46*	0.49**	NS	0.43*	NS	0.36*	0.73*	0.77**	0.56**	NS	0.71**	0.73**	0.75**	0.89**
University–5	0.55**	0.61**	0.49**	0.62**	0.61**	0.62**	0.79**	0.64**	0.68**	0.52**	0.76**	0.76**	0.75**	0.86**
University–6	0.61**	0.59**	NS	0.58**	0.54**	0.55**	0.75**	NS	NS	0.43*	0.41*	0.42*	0.41*	0.47**

*, ** : Significant at $p \leq 0.05$ and 0.01, respectively.

NS : Not significant.

Table 2. Dry–aggregate stability of air and oven–dry aggregates. The figures in parantheses show the number of aggregates crushed.

Soils	Air–dry Mean aggregate diameter, mm 22.22	 14.29	 7.14	 3.97*	Oven–dry Mean aggregate diameter, mm 22.22	 14.29	 7.14	 3.97*
Köprüköy Series	0.31(6)	0.92(26)	1.98(23)	7.54	0.38(6)	1.25(28)	2.18(28)	9.98
Uzunahmet Series	0.44(5)	1.07(25)	2.57(24)	13.86	0.51(5)	1.86(24)	3.49(30)	19.56
İspiryolu Series	0.46(5)	1.21(27)	3.80(27)	14.24	0.67(4)	1.83(29)	4.44(27)	19.04
Alaca Series	0.45(4)	1.15(28)	1.96(22)	13.41	0.47(4)	1.76(24)	3.60(23)	10.53
University–1	0.30(6)	0.56(24)	1.17(22)	5.32	0.43(6)	0.67(23)	3.35(23)	4.80
University–2	0.31(4)	1.05(28)	1.26(29)	4.29	0.44(4)	1.51(25)	2.33(29)	8.85
University–3	0.39(9)	0.76(27)	1.43(28)	10.51	0.43(7)	1.04(26)	2.29(28)	11.4
University–4	0.45(9)	0.95(25)	2.31(24)	7.81	0.47(7)	1.12(25)	2.41(28)	8.78
University–5	0.33(4)	1.11(28)	1.52(28)	4.23	0.35(4)	1.45(25)	2.74(28)	6.18
University–6	0.39(4)	1.08(28)	1.72(23)	4.94	0.41(4)	1.43(24)	2.31(24)	6.67

* : The number of aggregates in these groups was 30.

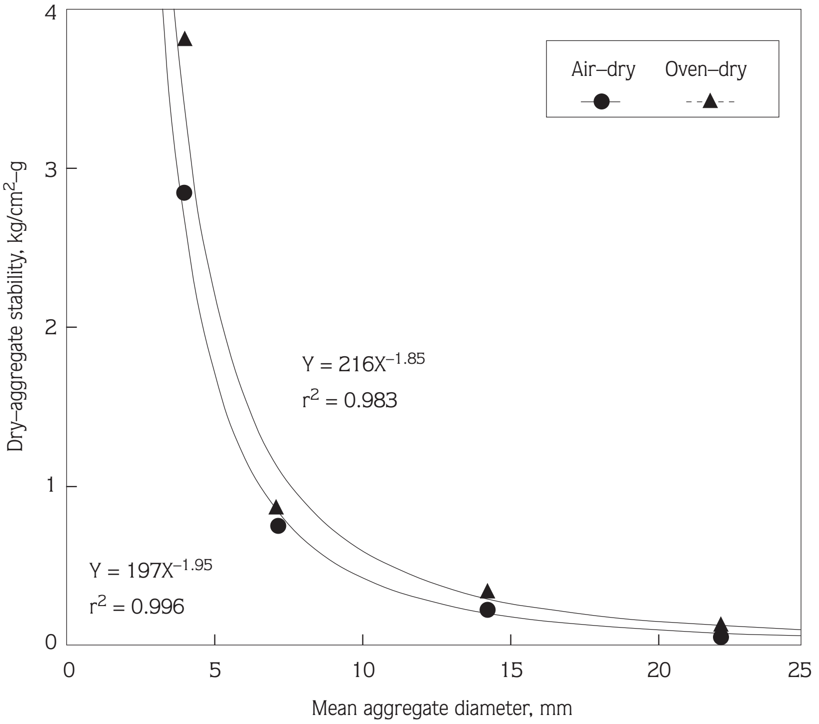

Figure 3. Dry–aggregate stability as a function of mean aggregate diameter.

cohesive forces between particles withstand the applied disruptive force (18), the strength of small aggregates may be due to strong bonds between particles. Under applied crushing stress aggregate deformation occurs at the weakest points. Thus, large aggregates may be broken into small aggregates. During the crushing test, it was noticed that some of the large aggregates were broken even under very small stresses and produced many small granular aggregates. Our results are supported by the results of Perfect and Kay (12) who emphasized that dry–aggregate strength decreased with the increasing size of aggregates.

As was expected, the dry–aggregate stability of air–dry aggregates was always smaller than those of oven–dry aggregates as a result of the strong cohesive forces between particles (Table 2). Measurement of aggregates in an air–dry state is not recommended because the small differences in aggregate water content which can occur with changing atmospheric relative humidity can have a significant effect on aggregate strength (13). In general, the variability in the penetrometer readings was higher for air–dry aggregates than oven–dry aggregates in the same size group. Therefore, the use of oven–dry aggregates may reduce errors when comparing the dry–aggregate stability of different soils.

Conclusions

The results of this study show that the strength of aggregates against applied mechanical forces was directly related to aggregate size and shape. As the size of an aggregate increased, the applied stress required to crush the aggregate was higher. The applied mechanical stresses necessary to break up to aggregate depended on the mass, volume, average diameter (D_{avg}) and geometric mean diameter (D_{gm}) of the aggregates being crushed. Dry–aggregate stability, defined as the applied stress per unit of mass, decreased with increasing mean aggregate diameter.

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