SEEDLING EMERGENCE AS INFLUENCED BY AGGREGATE SIZE AND BULK DENSITY

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ABSTRACT

Producers in western Canada are becoming increasingly interested in conservation tillage. A thorough understanding of how seedlings interact with the soil surrounding them is required to develop criteria for designing effective furrow openers and packing devices suitable for use in conservation tillage systems. To facilitate interpretation of the results of a field evaluation study of furrow openers for zero tillage seeders, we conducted a greenhouse experiment designed to assess the impact of bulk density and aggregate size distribution of the seedbed on the emergence of Hard Red Spring Wheat (*Triticum aestivum* L). Seeds of wheat (c.v. Lancer) were germinated in seedbeds with five aggregate size distributions with geometric mean diameter ranging from 0.44 to 12.67 mm, and four bulk densities ranging from 1.0 to 1.6 Mg m-3 arranged in a factorial design. The soil used in this study was taken from the Ap horizon of a Swinton silt loam (Orthic Brown Chernozemic). Number of seedlings emerged and speed of emergence were affected by bulk density and aggregate size of the seedbed, and by the interaction of both variables. In general increasing bulk density or aggregate size reduced and delayed emergence, but in seedbeds with high bulk density or with large aggregates, the effect of the other variable was negligible. Increased bulk density delayed emergence mainly by decreasing the volume of voids in the soil. This elevated the interfacial stress to the elongating coleoptile. The detrimental effect of increased aggregate size was mainly due to increase in the length of the path the coleoptile had to traverse to reach the soil surface, as it elongated through the interaggregate voids. Compaction of the seedbed to achieve the higher bulk densities in the coarser-aggregate seedbeds resulted in substantial breakdown of larger aggregates. Consequently, as the interfacial stress was increased by compaction, the path length was decreased, and both effects cancelled each other.

INTRODUCTION

Rapid and complete germination and emergence of wheat seeds improve the odds for obtaining good yields. Successful stand establishment is achieved by providing the seed with an environment which encourages early germination and emergence.

Although the seed environment comprises chemical, biological and physical components (Shaw 1952), the primary challenge in the design of seeding and planting equipment is in gaining adequate control of the physical components of the seed environment. Experience and intuition suggest that soil physical properties are the major determinant of seedling growth up to the time of emergence.

Seed germination commences after a period of imbibition, during which the seed takes up sufficient water to initiate growth. The rate of water uptake is controlled primarily by the hydraulic conductivities of the soil and seed epidermis, and by the extent of soil-seed contact. The critical soil water potential for wheat germination and emergence has been determined to be in the range of -900 KPa at 20°C to -600 KPa at 25°C (Lindstrom et al.

1976). Poor germination in soils at or near saturation has been related to reduction of oxygen diffusion through thick water films surrounding the seed (Dasberg and Mendel 1971).

The ease with which the water moves to the seed is determined largely by the structure of the seedbed. Research has shown that the optimum seedbed is composed of aggregates in the range of 1 to 5 mm diameter with up to 15% of fine material (<250 µm) that can block the larger pores (Russell, 1973). In addition to this, it is important that there is adequate seed-soil contact to facilitate water movement into the seed, and that there is adequate aeration. Most commonly adequate seed-soil contact is obtained by light packing with rollers or press-wheels. However, excessive pressure can lead to compaction of the seedbed, which can delay germination (Hadas 1985; Dexter 1988). In addition to this optimum environment for germination and early growth, that needs to exist only in the vicinity of the seeds, the seed-bed also must have larger aggregates near the surface, to prevent water losses, and wind and water erosion.

In semiarid zones wheat yields are often limited by poor stand establishment and low plant density (Bouaziz and Bruckler, 1989). Several authors have pointed out that some of the main factors affecting germination, emergence, and plant establishment in these environments are temperature, soil water potential, and mechanical characteristics of the seedbed (Schneider and Gupta, 1985; Bouaziz 1987). It has been shown that corn growth and yield reduction are well related with soil bulk density and penetration resistance (Rickman et al. 1965). Further, it has been established that wheat coleoptiles exert an average force of 0.30 N during elongation, with a range of 0.15 to 0.54 N (Bouaziz 1987; Souty 1987), and that final emergence percentages decrease linearly when resistances increased to above 0.24 N (Bouaziz 1987). Experimental studies on limiting soil strength conditions for wheat emergence have shown that germination, root elongation, coleoptile elongation, and emergence of wheat can be affected by interfacial stresses larger than 3.0, 2.3, 1.7, and 0.8 MPa respectively (Collis-George and Yoganathan 1985). Emergence of barley (*Hordeum vulgare* L) was reduced in soils with penetrometers resistances greater than 2.50 MPa (Ball and O'Sullivian 1982).

The objective of this study was to determine the effects of aggregate size distribution, and bulk density above the seed on the speed of germination and germination of spring wheat on a medium textured soil.

MATERIALS AND METHODS

Hard Red Spring Wheat seeds (c.v. Lancer) were germinated in a greenhouse under five aggregate size distributions and four different bulk densities. The soil used was the Ap horizon (0-10 cm) of a Swinton silt loam (Ayres et al., 1985).

Soil samples were air-dried, large clods were gently broken into medium-sized clods by hand pressure, and aggregates were separated into 7 size fractions with a rotary sieve (Chepil and Bisal 1943). The aggregates classes obtained with this process were: smaller than 0.42 mm, 0.42 to 0.83 mm, 0.83 to 2.00 mm, 2.00 to 6.40 mm, 6.40 to 12.76 mm, 12.76 to 38.00 mm, and larger than 38.00 mm.

Water aggregate stability was determined in aggregates 1.00 to 2.00 mm by wet sieving using the process described by Kemper and Rosenau (1986).Prior to wet sieving the aggregates were either pre-wetted by a mist of a humidifier or not pre-wetted. This simulated the effects of the rainfall on a dry soil and in a soil previously wetted.

Five aggregate size distributions were prepared by mixing aggregate appropriate amounts of different aggregate to obtain aggregate geometric mean diameters (GMD) of 0.44, 1.48, 2.96, 6.16, and 12.67 mm. Mixing of the aggregates was done separately for each of the classes. Treatments consisted of a factorial combinations of the five aggregates classes described earlier and four bulk densities (i.e., 1.00, 1.20, 1.40, and 1.60 Mg m-3).

The soil was placed in wooden containers of (400 x 350 x 105 mm) lined with polyethylene with perforations in the bottom. Enough soil of 2.96 mm GMD, representative to the aggregate size distribution in the field, was placed in the bottom of the containers through a large plastic funnel to prevent aggregate segregation. This layer of soil was packed by gently tapping with a piece of wood, until a 4 cm soil layer with a bulk density of 1.30 Mg m^{-3} was obtained.

Six rows separated 65 mm were made on the surface of this 4 cm layer, using a special plate. Fifteen seeds of spring wheat (94% germination) were placed at 20 mm interval on each row and firmly pressed to ensure good soil-seed contact. After placing the seeds, a layer of soil 5 cm thick of the five different GMD classes was placed on the top and packed to obtain any of the four desired bulk densities. The filling and the packing of the top layer was done as it was for the bottom layer, except for the 1.40 and 1.60 Mg m^{-3} densities that had to be packed with a plunger to obtain the desired densities.

Two plastic tubes (2 inches inside diameter) were inserted near opposite corners of the boxes, and enough water to bring the soil to a water content equivalent to field capacity, was added slowly through the plastic tubes. After irrigation, the boxes were covered with clear polyethylene film to minimize moisture loss during the study.

Plant emergence was determined by counting the number of seedlings emerged in each row three times daily. The speed of emergence (SOE) (Tessier, 1988), mean emergence date (MED), emergence rate index (ERI), and percent emergence (PE) (Bilbro and Wanjura, 1982) were calculated as follows :

$$SOE = \frac{N_1 + N_2 + \cdots + N_n}{t_1 + t_2 + \cdots + t_n} \qquad PE = \frac{N_n}{N_s} 100$$

$$MED = \frac{N_1 t_1 + N_2 t_2 + \cdots + N_n t_n}{N_1 + N_2 + \cdots + N_n} \qquad ERI = \frac{N_n}{MED}$$

where : N_1, N_2,...N_n is the number of newly emerged seedlings at times t_1, t_2,...t_n, and N_s is the number of seeds planted in each row.

After emergence had ceased, the trays were uncovered and left to dry . Soil resistance to penetration in the seed rows was measured with a needle penetrometer furrow strength meter (Dyck et al. 1993). The needle probes were inserted into the soil to a depth of 50 mm and the penetration resistance was recorded every 0.30 mm.

After measurement of penetration resistance, two cores 50.8 mm in diameter and 50 mm deep were taken from each tray. Bulk density (db) and aggregate size distribution of each core was determined.

RESULTS & DISCUSSION

This soil has relatively low soil organic matter (1.93% organic C), and silt is its predominant particle size (50.4%). It has 31.4% sand and 18.2% clay. The moisture content at -303 KPa and -1520 KPa were 25 and 11%, respectively. The bulk density in the field was 1.3 Mg m^{-3}, and the aggregate distribution was dominated by aggregates larger than 2 mm and by aggregates smaller than 0.42 mm. Due to its relatively low organic matter and high content of silt, this soil is propense to dispersion by rain drops and to sealing and crusting. This was evident from the results of the wet sieving procedure. When the aggregates were slowly pre-wetted by a fine mist more than 90% of the aggregates were stable. However, when the soil was not pre-wetted, to simulate the effect of rain showers on a dry soil, less than 15% of the aggregates were stable. The structure of this soil can be

Table 1.- Comparison of planned and measured bulk density, aggregate size distribution and geometric mean diameter (GMD) of the aggregate mixtures used in the study.

Bulk Density		Aggregate classes (mm)						GMD	
Plan.	Meas.	< 0.42	0.42-0.83	0.83-2.0	2.0-6.4	6.4-12.7	12.7-38.0	Plan.	Meas.
— Mg m-3 —		(percent by weight)						mm	
1.00	1.01	57.1	21.9	16.0	5.0	0	0	0.44	0.42
1.20	1.18	60.3	18.8	17.4	3.5	0	0	0.44	0.40
1.40	1.39	57.0	18.8	17.8	6.4	0	0	0.44	0.44
1.60	1.57	52.4	14.2	21.9	11.5	0	0	0.44	0.53
Planned distribution		50.0	25.0	25.0	0	0	0		
1.00	1.00	22.4	18.4	33.0	13.6	8.7	3.9	1.48	1.22
1.20	1.18	28.0	18.2	30.8	14.1	8.2	0.6	1.48	1.00
1.40	1.42	33.5	14.7	22.7	17.0	6.9	5.3	1.48	1.06
1.6	1.56	35.0	14.5	26.7	17.0	4.4	2.5	1.48	0.90
Planned distribution		8.5	16.5	50	16.5	8.5	0		
1.00	0.99	25.6	5.5	6.6	13.2	9.3	39.8	2.96	3.61
1.20	1.21	22.9	4.3	6.4	13.7	10.8	41.9	2.96	4.21
1.40	1.42	31.4	6.5	9.4	20.2	14.1	26.6	2.96	2.25
1.60	1.61	24.6	5.1	9.4	20.2	14.1	26.6	2.96	2.98
Planned distribution*		26.6	5.6	9.2	16.5	10.2	31.8		
1.00	0.97	10.2	2.8	7.0	19.4	19.2	41.4	6.16	6.70
1.20	1.20	7.2	2.4	6.6	20.6	21.6	41.6	6.16	7.59
1.40	1.38	12.9	4.8	13.6	26.8	16.9	25.0	6.16	4.04
1.60	1.59	14.9	4.2	10.8	25.8	17.8	27.0	6.16	4.15
Planned distribution		0	0	25.0	25.0	25.0	25.0		
1.00	0.96	4.5	1.4	3.7	18.4	18.7	53.3	12.67	10.40
1.20	1.16	3.3	0.4	1.6	16.3	23.1	55.3	12.67	12.10
1.40	1.37	5.4	0.9	2.8	18.9	23.3	48.7	12.67	9.90
1.60	1.55	15.3	3.0	7.3	29.0	19.2	26.2	12.67	4.30
Planned distribution		0	0	0	25.0	25.0	50.0		

* Aggregate distribution in the field

seriously destroyed by fast wetting the soil when it is dry and it can be even more seriously destroyed if it is subjected to compression or shearing forces when wet.

The coarse aggregate mixtures required substantially more pressure to achieve the 1.40 and 1.60 Mg m-3 density levels than the finer aggregate mixtures. The final aggregate distributions revealed that there was substantial breakdown of the coarser aggregates. This was evidenced by the appearance of aggregates finer than 0.83 mm in the 6.16 and 12.67 mm GMD mixtures (Table 1). Under these conditions, only regression analysis could be

Table 2.- Effect of aggregate geometric mean diameter (GMD) and bulk density (DB) of the seedbed on percent emergence (PE), means emergence date (MED), emergence rate index (ERI), speed of emergence (SOE), work (WRK), penetration resistance (PR) and void ratio index (VRI).

GMD	DB	PE	MED	ERI	SOE	WRK	PR	VRI
(mm)	(Mg m^{-3})	(%)	(day)	– (plant day^{-1}) –		(Joule)	(MPa)	
0.42	1.01	93	6.64	10.99	1.86	0.43	0.95	1.63
0.40	1.18	87	7.07	9.90	1.67	0.37	0.67	1.27
0.44	1.39	82	7.94	8.56	1.44	0.79	1.41	0.89
0.53	1.57	70	9.03	6.53	1.10	1.06	1.76	0.69
1.22	1	97	6.66	11.11	1.89	0.27	0.50	1.63
1.00	1.18	87	7.15	9.65	1.63	0.39	0.60	1.27
1.06	1.42	93	7.74	8.78	1.47	0.88	1.27	0.89
0.90	1.56	82	8.48	7.90	1.34	1.35	1.91	0.69
3.61	0.99	98	7.20	10.69	1.88	0.35	0.63	1.70
4.21	1.21	85	8.10	8.51	1.47	0.64	1.07	1.17
2.25	1.42	78	8.00	7.78	1.33	0.76	1.26	0.89
2.98	1.61	90	9.53	7.14	1.22	1.26	2.09	0.64
6.70	0.97	75	7.07	8.90	1.54	0.37	0.65	1.70
7.59	1.2	95	7.49	9.07	1.57	0.38	0.77	1.22
4.04	1.38	88	8.24	9.22	1.57	0.87	1.36	0.92
4.15	1.59	77	9.00	7.33	1.24	1.61	2.60	0.67
10.44	0.96	82	7.50	8.40	1.49	0.35	0.78	1.78
12.11	1.16	80	8.86	7.22	1.27	0.52	1.00	1.27
9.90	1.37	80	7.80	8.08	1.36	0.98	1.80	0.92
4.32	1.55	55	9.36	5.56	0.98	1.44	2.26	0.69

used to evaluate the effect of bulk density and aggregate size distribution.

Porosity of the seedbed, as estimated by void ratio index, decreased with increases in bulk density by similar amounts over all the aggregate classes (Table 2). The compaction of the aggregate mixtures reduced the volume of voids in the soil. In the finer-aggregate mixtures this was accomplished mainly by a rearrangement of the aggregates, while in the coarser mixtures there was a breakdown of the larger aggregates into smaller ones that occupied the voids among the larger aggregates. As indicated previously, when comparing the aggregate size distribution at the end of the study with that of the original mixtures revealed that for all aggregates classes, except the finer one, there was a substantial increase in the proportion of finer aggregates with a corresponding decrease in the proportion of coarser aggregates (Table 1).

Although aggregate size distribution had no significant effect on soil porosity, the average penetration resistance of the layer covering the seed, and the work exerted to push the needle into the soil, was affected by both bulk density and aggregate size distribution, and by the interaction of both variables (Table 2). Regression analysis revealed that bulk density, the square of bulk density, GMD of the aggregates and the interaction between bulk density and GMD accounted for 94% of the variability observed in penetration resistance and work (Table 3). In general penetration resistance and work increased in a parabolic form with increasing bulk density; the effect of GMD was small at low values of bulk density, but it became progressively larger as bulk density increased (Figure 1).

Table 3.- Regression equations showing the relationship between various measured variables with geometric mean diameter (G) and bulk density (D) of the seedbed.

Variable	Regression equation	R^2	RMSE†	Prob > F
ERI*	$18.9 - 0.87\,G - 7.48\,D + 0.56\,G \cdot D$ (1.4)◊ (0.29) (1.08) (0.24)	0.83	0.66	< 0.0001
MED	$3.0 + 0.09\,G + 3.54\,D$ (0.6) (0.03) (0.42)	0.81	0.41	< 0.0001
SOE	$3.2 - 0.13\,G - 1.27\,D + 0.08\,G \cdot D$ (0.2) (0.05) (0.18) (0.04)	0.84	0.11	< 0.0001
PE	$110 - 20.4\,D$ (12) (9.3)	0.21	9.3	0.04
PR	$6.7 - 0.20\,G - 11.0\,D + 5.05\,D^2 + 0.20\,G \cdot D$ (1.8) (0.08) (2.8) (1.07) (0.07)	0.94	0.17	< 0.0001
WRK	$3.7 - 0.10\,G - 6.40\,D + 3.05\,D^2 + 0.09\,G \cdot D$ (1.2) (0.05) (1.90) (0.72) (0.05)	0.94	0.12	< 0.0001

◊ Figures in parenthesis are standard error of estimates shown immediately above

Table 4.- Linear relationships between several emergence estimators and penetration resistance of the seedbed

Variable	Regressor estimates for relationship $Y = B_0 + B_1\,PR$		R^2	RMSE†	Prob > F
	B_0	B_1			
ERI*	10.8 (0.51)◊	-1.79 (0.30)	0.57	0.98	0.0001
MED	6.45 (0.26)	1.12 (0.18)	0.69	0.50	< 0.0001
SOE	1.87 (0.08)	-0.32 (0.06)	0.62	0.16	< 0.0001
PE	95.4 (4.5)	-9.2 (3.2)	0.31	8.6	0.01

† Root mean square of the error
* ERI Emergence rate index (plant day^{-1})
MED Mean emergence date (day)
SOE Speed of emergence (plant day^{-1})
PE Percent emergence
◊ Figures in parenthesis are standard error of estimates

Standardized estimates indicated that changing the bulk density by one standard deviation produced changes in penetration resistance roughly ten times those produced by changes in one standard deviation in GMD. Disruption of the aggregates by compaction led not only to a higher bulk density, but also to a more pronounced consolidation and more internal

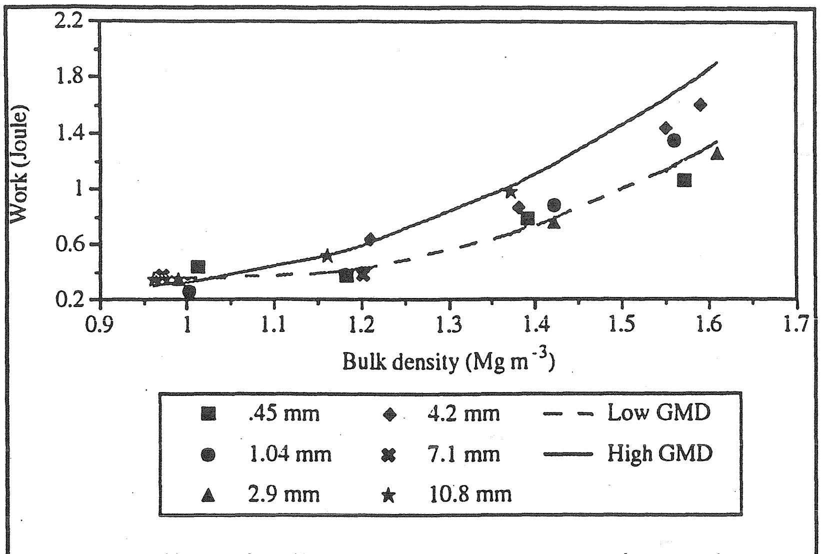

Figure 1. Effect of bulk density and aggregate size on the work excerted by the penetrometer needles

friction and cohesion between the aggregates. Consequently the effect of bulk density was more pronounced than the effect of GMD on penetration resistance and work values. These results are similar to the findings of Busscher and Lipiec (1993) who found that at every level of bulk density they tested, the resistance to penetration of the seedbed was higher in coarse- than in fine-aggregate seedbeds. Cohesion and friction within aggregates is higher than among aggregates; therefore, penetrometer resistance in a structured soil result in periodic high and low readings as the peneterometer needle passes through aggregates and voids, respectively (Hadas and Schmulevich 1990). Thus, the average penetration resistance of a coarse-aggregate seedbed would be higher than that of a fine-aggregate seedbed of similar density. Evidence of this is presented in Figure 2 that shows little difference in the penetration resistance profiles of a fine- and coarse-aggregate mixture at low bulk density, but large differences on the profiles of a fine- and a medium-aggregate seedbed at high bulk density.

Both total emergence and speed of emergence were affected by average penetration resistance of the seedbed (Table 4). However, the percent emergence was much less affected by penetration resistance than any of the of the indicators of speed of emergence. Increase of 1 MPa in penetration resistance delayed MED by slightly more than one day, and reduced percent emergence by 9%.

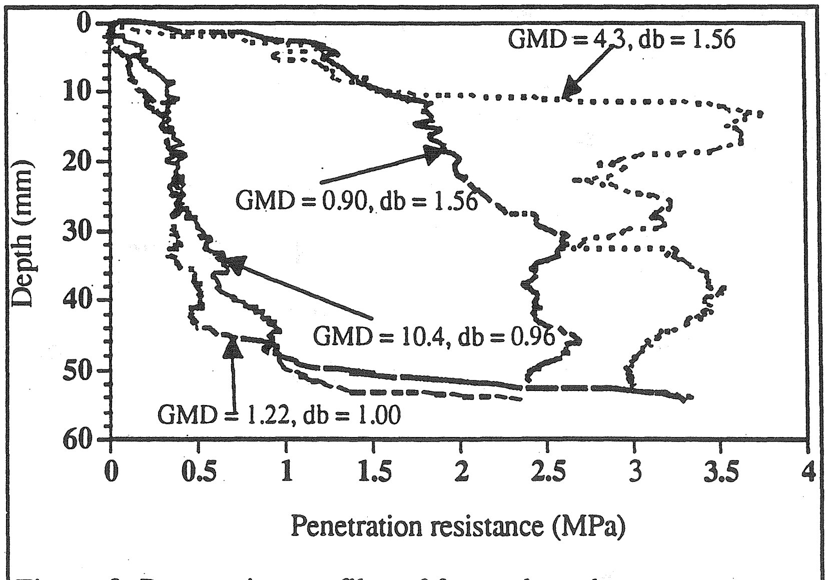

Figure 2. Penetration profiles of four selected treatments

As germination was delayed there was an increase in the number of seedlings that failed to emerge. This indicated that as seedbed conditions delayed germination there was an increasingly larger proportion of seedlings that stopped elongation of their coleoptiles, probably because of insufficient energy reserves in the seed to sustain prolonged growth. A linear regression between SOE and PE indicated that on average PE was reduced by 33% (± 6) per unit decrease in SOE (P = 0.001) (data not shown).

Emergence was delayed by increases in bulk density and GMD. A linear model with bulk density, GMD, and their linear interaction explained about 83% of the observed variability in the indicators of speed of emergence (Table 3). In fine-aggregate seedbeds ERI decreased linearly with increases in bulk density. This indicates that as the voids between aggregates became smaller due to compaction, the elongating coleoptile was subject to an increased interfacial resistance that slowed down its rate of elongation. Cursory observations revealed that under low bulk density, the coleoptiles were able to move and rearrange small aggregates, while under higher levels of bulk density they were not able to rearrange the aggregates as easily. These observations are in agreement with previous studies that showed that during elongation, wheat coleoptiles were able to exert and average force of 0.30 N (Bouaziz 1987; Souty 1987), and that coleoptile elongation can be perturbed by interfacial stresses larger than 1.7 MPa (Collis-George and Yoganathan 1985).

In coarse aggregate seedbeds, emergence was reduced and delayed, regardless of bulk density levels. Because the coleoptiles elongated into the interaggregate voids, the length of the path between the seed and the soil surface was greatly lengthened in the coarse-aggregate seedbed. Consolidation of the seedbed at higher bulk densities had only marginal effect on the speed of emergence. As explained earlier, larger aggregates broke down into smaller ones as pressure was applied to obtain the desired bulk density levels. Therefore, as the bulk density increasd, the volume of void spaces was reduced with a consequent increase in interaggregate friction, but at the same time the path from the seed to the soil surface was reduced due to aggregate breakdown. The effect of these two factors on emergence is counteracting so their overall effect was nil.

CONCLUSIONS

From the standpoint of germination and seedling emergence, a good seedbed must provide physical conditions conducive to maximize the speed of water transfer from the soil to the seed, total emergence, and speed of emergence. In general terms these objectives can be achieved in seedbeds with low bulk density and small aggregates. Furthermore, the seedbed must protect the seedling against dehydration, and damage by wind and water erosion. However, in most circumstances these are conflicting objectives. For example, the transfer of water from the soil to the seed is maximized when there is good soil-seed contact, which is achieved by lightly packing soil around the seed. However these conditions also increase the rate of water loss from the furrow area, and tend to slow down seedling emergence by increasing interfacial stress. Protection against wind and water erosion can be achieved by having large aggregates that are more resistant to disintegration. However this increases the path length for the coleoptile and delays emergence.

In summary, an ideal furrow opener should provide adequate packing of the seed against a fine-aggregate bed to maximize water transfer, should cover the seed with a loose layer of fine aggregates that would foster fast seedling emergence, and should deposit a loose layer of coarse aggregates at the surface of the soil to protect against erosion and would present a barrier against capillary movement of water to prevent desiccation of the soil surrounding the seed.

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