Studies on the Lethal Effect of the So-called "Inert" Pulverized Materials upon Insects. (VII)*

On the Lethal Effect of Carborundum Powder on Adults of the Azuki Bean Weevil, *Callosobruchus chinensis* L., With Special Reference to the Relation Between the Lethal Effect and the Particle Diameter

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From the statistico-physiological point of view, the data on the lethal effect of carborundum powder to adults of the azuki bean weevil were analysed. On the basis of the result of the statisitical analysis, the writer tried to prove the appropriateness of the abrasion theory for the interpretation of the mechanism of lethal effect of the so-called "inert" pulverized materials on insects.

INTRODUCTION

It has been known for a long time empirically that the so-called chemically "inert" pulverized materials such as talc, bentonite, diatomaceous earth etc. have the lethal effect upon some kind of insects under certain conditions. And now, we can point out a considerable number of papers either of the fundamental studies on the mechanism of its lethal action or of the economic studies on its practical application. The abrasion theory advanced by Alexander et al.,[1] Parkin,[21] Wigglesworth[29,30,31] and others, to the effect that impermeability of insect cuticle to water is broken by the abrasion of inert dusts and that the death is caused by the rapid loss of body water, is accepted by majority of investigators as the most approriate theory. In this paper, the writer wishes to describe the results of experiments carried out to investigate the relation between the lethal effect of carborundum powder to adults of the azuki bean weevil, *Callosobruchus chinensis* L., and its particle diameter under the environmental condition of 30°C and 73, 91 and 100 % relative humidity, and to examine the abrasion theory from the statistico-physiolo-

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gical point of view.

MATERIAL AND INSECT

Carborundum powder: Carborundum powders of eight degrees of fineness used in the experiment were products of the Fujimi Kōgyo Co. Ltd., Nagoya, Japan. They belong to the green carborundum powder group and are called "*GC*" commercially for brevity's sake. They assume a pale grey green colour and have a glassy lusture. Under the microscope we can see their irregular shapes with many sharp edges. As shown in Table 1, carborundum powder consists of 96.5 per cent

Table 1. Chemical analysis of carborundum powder.[10]

SiC	96.5 %
Fe	0.3 <
Al	0.5 <
CaO + MgO	1.0 <
SiO_2	1.0 <
C	0.5 <
Si	0.5 <

silicon carbide and a little quantities of some other materials. And it has a specific gravity of 3.16~3.24. Average diameters of these carborundum powders shown in Table 2, were determined photomicrographically. Namely the length of the longest axis (long diameter) and that of the maximum diameter which meets at right angle to it were measured on individual particles in the microphotograph. The average of these two measurements was taken for the average diameter. The figures of Table 2 are the mean diameter determined by measuring more than 200 particles of eight degrees of fineness respectively. Before being used in the experiment these powders were dried throughout for 5 hours in an electric heat chamber which is maintained at 110°C. Then, they were kept in the desiccator with amorphous calcium chloride until they were used for experiment.

Azuki bean weevil: Azuki bean weevil, *Callosobruchus chinensis* L., used in this experiment belongs to the strain of Entomological Laboratory, College of Agriculture, Kyoto University, which have been reared already for more than ten years by inbreeding a small number of normal individuals. Therefore these individuals can be considered to be a pure strain having the same genetical structure so that it may be expected that they are quite homogeneous in physiological as well as in morphological characters. A modified Zwölfer's apparatus[27] used for culture of the weevils consists of a set of petri dishes 8.5 in inner diameter and 1.8

Table 2. Degrees of fineness and average diameter D (μ) of carborundum powders determined from photomicrograph.[10]

Degrees of fineness	Average diameter
# 240	67.0±3.5
# 320	48.0±2.5
# 500	34.0±1.8
# 700	24.0±1.3
# 1000	16.0±1.1
# 1500	10.0±0.7
# 2000	7.9±0.5
# 3000	5.0±0.4

cm in height. That is, the upper and lower dishes were separated with a piece of muslin. Under the condition of temperature 30°C the relative humidity in the upper dish was maintained at 73 % by the super saturated solution of sodium chloride in the lower dish. The azuki bean, *Phaseolus angularis* Wight, on which weevils were reared was the variety "Uda-Dainagon" produced in Uda district of Nara prefecture. And its water content was 15 %. Twenty pairs of weevils and 20 grams of azuki beans were placed in this petri dish for the oviposition. And the dishes were laid in the dark incubator maintained at 20°C electrically. After about three weeks, the progeny begin to emerge and the emergence continues for about five days. About five hundred weevils can be obtained easily from one set of the dishes. The writer selected for use healthy individuals of uniform size emerged within 12 hours before the test.

APPARATUS AND METHOD

The apparatus used for experiment is shown in Figure 1. The procedure is as follows: first, a petri dish 9 cm in inner diameter and 5 cm in height containing the super saturated salt solution was covered with a piece of muslin, which was fastened to the dish with a rubber band.

Five glass cells 2.7 cm in diameter and 3.0 cm in height were placed bottom upward on this muslin cover. Then the glass cells were covered with a petri dish of just the same size as the lower dish. The super saturated solutions of sodium chloride and potassium nitrate and distilled water were used to keep the relative humidities in the glass cell at 73, 91 and 100 % respectively. The figures of relative humidity, 73, 91 and 100 % are not the results of the writer's measurement; they were adopted from the Zwölfer's paper.[35]

Healthy adult weevils were first grouped into female and male individuals. One hundred individuals at a time were placed in a pair of small petri dishes 5.5 cm in inner diameter and 1.5 cm in height containing the carborundum powder to

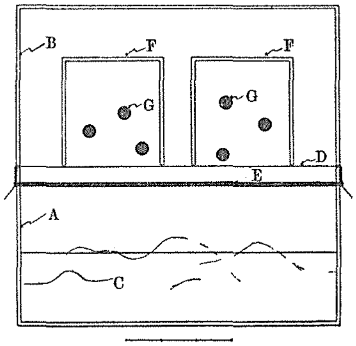

Fig. 1. Experimental apparatus. A and B, petri dish ; C, super saturated salt solution ; D, muslin ; E, rubber band ; F, glass cell ; G, azuki bean weevil. 1 unit=1cm.

be tested. The petri dishes were shaken gently two or three times and left standing for a little while. In this procedure, the insects were coated heavily with the carborundum powder. After being coated with the powder, ten individuals were placed in a small glass cell with the help of pincett. And the whole experimental apparatus was placed in a dark incubator regulated at 30°C electrically. Every day, the live or dead weevils were counted at the prescribed time. The weevils which did not show no response to any stimulus were regarded as dead individuals and this observation was continued until all the weevils were dead. In the tests at 73 and 100 % relative humidities, 200 individuals of females and males were used for each series. The same number of individuals was used in controls. And in the test at 91 % relative humidity, 500 individuals of females and males were used for each series and the same number of individuals was used in controls.

RESULT AND DISCUSSION

The results of experiments represented as the relation between the time T (day) and the cumulated mortality Y (%) for each series are shown in Table 3. This investigation was carried out in the duration from November 1948 to October 1950.

First, the writer wishes to consider the relation between time and mortality taking the experimental result obtained at 73 % relative humidity with carborundum powder of ♯700 degree of fineness as an example. When the cumulated percentages were plotted on the ordinate and the time on the abscissa nearly symmetrical sigmoid curves were obtained in both cases of female and of male as shown in Figure 2. The graph shows that these curves can be converted to straight lines by transforming the cumulated mortalities to a function of the normal curve such as the probit and without transforming the time to logarithms. The result converted the time-mortality curves to straight line was shown in Figure 3. On the basis of the

Table 3. Time T (day)-mortality Y(%) of adults of the azuki bean weevil, *Callosobruchus chinensis* L., treated with carborundum powders of various degrees of fineness.

Relative humidity %	Sex	Degree of fineness	Number of individuals	Time 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
73	Female	# 240	200	1.5	2.5	8.5	13.5	18.0	25.0	44.5	69.0	82.0	93.5	98.0	100.0	—	—	—
		# 320	200	0.0	6.0	8.0	10.5	12.5	19.5	41.0	65.0	83.5	95.5	99.0	100.0	—	—	—
		# 500	200	0.0	7.0	11.5	15.5	21.5	39.5	58.0	84.0	93.5	98.5	100.0	—	—	—	—
		# 700	200	1.0	2.0	5.0	9.0	25.5	45.5	61.5	77.5	87.5	96.0	98.5	100.0	—	—	—
		#1000	200	0.0	1.0	5.5	16.5	29.0	43.5	67.5	82.5	95.5	99.0	100.0	—	—	—	—
		#1500	200	0.0	3.0	10.5	21.5	37.5	65.0	78.5	94.0	99.5	100.0	—	—	—	—	—
		#2000	200	0.0	0.5	5.0	33.5	55.0	76.0	91.0	99.5	100.0	—	—	—	—	—	—
		#3000	200	1.0	9.0	19.5	34.0	61.5	90.5	99.0	100.0	—	—	—	—	—	—	—
		Control	200	0.5	2.5	3.5	7.0	19.5	34.0	53.0	65.0	81.5	97.0	98.5	100.0	—	—	—
	Male	# 240	200	0.5	1.5	7.5	21.0	42.0	67.5	80.0	93.0	98.5	100.0	—	—	—	—	—
		# 320	200	1.5	5.5	12.5	22.0	37.0	62.0	79.5	92.0	100.0	—	—	—	—	—	—
		# 500	200	0.0	3.0	9.0	23.0	52.0	70.5	91.0	99.0	100.0	—	—	—	—	—	—
		# 700	200	1.0	4.5	13.0	33.0	51.5	74.0	91.0	97.5	99.5	100.0	—	—	—	—	—
		#1000	200	0.0	4.5	18.0	34.0	68.5	92.5	98.5	100.0	—	—	—	—	—	—	—
		#1500	200	1.0	10.5	28.5	70.0	88.0	96.0	100.0	—	—	—	—	—	—	—	—
		#2000	200	0.0	6.5	36.5	64.0	75.0	90.5	99.0	100.0	—	—	—	—	—	—	—
		#3000	200	5.5	27.0	42.5	66.5	88.5	98.5	100.0	—	—	—	—	—	—	—	—
		Control	200	0.0	1.5	7.0	23.5	53.0	67.5	77.5	88.0	95.5	100.0	—	—	—	—	—
91	Female	# 240	500	0.0	0.2	0.8	1.2	3.4	9.0	22.4	41.6	63.8	82.0	92.8	98.0	99.0	100.0	—
		# 320	500	0.0	0.4	0.8	1.8	3.8	10.2	23.8	52.4	69.4	84.0	93.2	97.2	98.0	99.6	100.0
		# 500	500	0.0	0.2	0.6	2.2	5.6	18.0	35.4	59.8	81.0	93.2	93.0	99.4	100.0	—	—
		# 700	500	0.0	0.0	1.8	7.6	17.2	32.0	57.0	74.0	89.4	96.4	98.6	99.8	100.0	—	—
		#1000	500	0.6	1.8	3.2	8.2	22.4	44.6	68.4	85.4	95.4	99.0	99.8	100.0	—	—	—
		#1500	500	0.0	1.0	2.6	7.8	28.8	66.2	90.0	99.2	99.4	100.0	—	—	—	—	—
		#2000	500	0.2	1.0	3.0	13.8	45.2	71.4	89.4	95.8	99.2	100.0	—	—	—	—	—
		#3000	500	0.4	2.2	6.0	26.2	70.0	82.0	94.6	99.0	100.0	—	—	—	—	—	—
		Control	500	0.0	0.0	0.0	0.8	2.6	7.4	22.8	49.6	68.4	83.0	92.4	97.2	99.0	99.8	100.0
	Male	# 240	500	0.2	0.6	2.4	4.0	9.8	26.4	46.4	69.6	82.2	93.0	97.0	98.8	99.6	100.0	—
		# 320	500	0.0	1.4	5.4	13.2	22.4	43.6	64.2	82.4	91.6	96.8	99.6	99.8	100.0	—	—
		# 500	500	0.2	0.8	2.2	6.6	14.8	37.8	57.8	79.4	92.4	98.4	99.6	100.0	—	—	—
		# 700	500	0.2	1.0	3.2	11.8	29.6	59.0	74.0	89.8	98.4	99.6	100.0	—	—	—	—
		#1000	500	0.2	1.8	7.2	17.8	34.8	64.8	86.2	98.0	99.8	100.0	—	—	—	—	—
		#1500	500	0.0	2.6	9.6	26.6	65.6	87.2	98.4	99.8	100.0	—	—	—	—	—	—
		#2000	500	0.2	3.2	10.0	34.6	72.2	88.8	96.2	99.0	100.0	—	—	—	—	—	—
		#3000	500	1.2	3.4	34.4	70.6	91.4	99.0	99.8	100.0	—	—	—	—	—	—	—
		Control	500	0.0	1.8	3.0	5.8	17.2	33.0	52.6	72.4	88.0	94.8	98.2	99.2	99.8	99.8	100.0
100	Female	# 240	200	0.0	0.0	0.5	0.5	2.0	9.5	23.0	43.5	67.5	84.0	94.5	98.5	99.5	100.0	—
		# 320	200	0.0	0.0	0.0	0.5	1.0	10.0	22.5	47.0	70.5	92.0	97.5	100.0	—	—	—
		# 500	200	0.0	1.0	2.0	3.5	7.5	17.0	40.0	66.0	79.5	88.5	97.0	99.5	100.0	—	—
		# 700	200	0.0	0.0	0.0	4.5	11.5	29.0	57.0	77.5	92.0	97.0	100.0	—	—	—	—
		#1000	200	0.0	0.0	0.5	3.5	11.0	44.0	77.0	97.0	99.0	99.5	100.0	—	—	—	—
		#1500	200	0.0	1.0	6.5	14.5	30.5	57.5	81.0	93.5	97.5	99.5	100.0	—	—	—	—
		#2000	200	0.5	2.5	6.5	26.0	52.5	74.0	91.5	98.0	99.0	99.5	100.0	—	—	—	—
		#3000	200	0.5	3.0	11.5	47.5	75.5	87.0	95.5	99.5	100.0	—	—	—	—	—	—
		Control	200	0.0	0.0	0.0	0.0	7.0	23.0	42.5	73.5	84.0	94.5	99.5	100.0	—	—	—
	Male	# 240	200	0.0	0.0	2.0	4.5	7.5	22.0	42.0	61.0	79.0	83.0	96.5	99.5	100.0	—	—
		# 320	200	0.0	0.0	3.0	6.0	19.0	30.0	50.5	70.0	87.0	97.0	98.0	99.5	100.0	—	—
		# 500	200	0.0	2.0	2.5	9.0	18.5	41.5	66.5	86.0	96.0	99.0	100.0	—	—	—	—
		# 700	200	1.0	6.0	14.0	23.0	37.5	55.0	77.0	89.5	97.5	100.0	—	—	—	—	—
		#1000	200	1.0	2.5	8.0	27.5	51.0	72.0	89.0	97.0	99.5	100.0	—	—	—	—	—
		#1500	200	0.0	4.0	17.0	40.0	62.5	81.0	96.5	97.5	99.5	100.0	—	—	—	—	—
		#2000	200	1.5	6.0	21.5	41.0	58.5	82.5	94.5	99.5	100.0	—	—	—	—	—	—
		#3000	200	3.0	12.0	42.0	76.0	94.0	98.0	100.0	—	—	—	—	—	—	—	—
		Control	200	0.0	0.5	2.5	14.5	27.5	49.0	71.5	84.5	94.5	98.0	100.0	—	—	—	—

idea obtained in this graphic analysis, the writer summarized the data in table 3 by applying the computation method of rectified time-mortality curve described by Bliss.[4] The results are shown in table 4.

When we compare the lethal times of treated lots with those of untreated lots

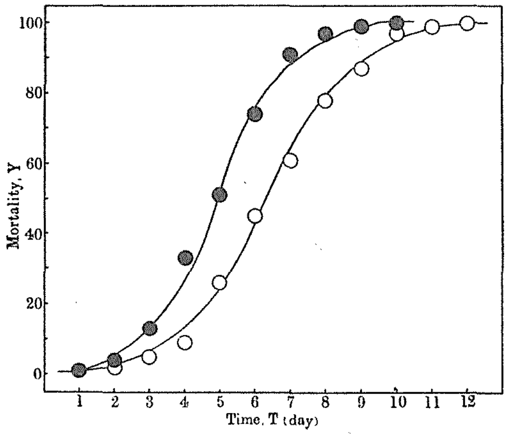

Fig. 2. Time-mortality graph of adults of the azuki bean weevil, *Callosobruchus chinensis* L., for carborundum powder of #700 degree of fineness. Solid line with hollow circles represents female and solid line with solid circles represents male.

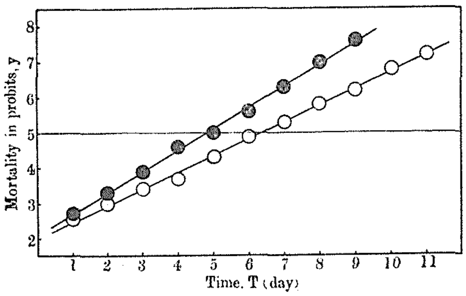

Fig. 3. Time-mortality regression lines of adults of the azuki bean weevil, *Callosobruchus chinensis* L., for carborundum powder of #700 degree of fineness. Solid line with hollow circles represents female and solid line with solid circles represents male.

in Table 4 we can recognize easily that the carborundum powder has not a little lethal effect upon insects. The lethal effect upon insects of carborundum powder was already reported by Alexander et al.,[1] Briscoe[6] working with the rice weevil, *Sitophylus oryzae* L., Yasue[34] with the small rice weevil, *Sitophylus sasakii* Takahashi, David and Gardiner[8] with the granary weevil, *Sitophylus granarius* (L.), the red flour beetle, *Tribolium castaneum* (Herbst), the lesser grain borer, *Rhizopertha domica* (F.) and the Australian spider beetle, *Ptinus tectus* Boield, and Nagasawa[17,19,20] with the azuki bean weevil. Since the particles of carborundum powder have sharply pointed angles and are very hard as has been stated above, it is easily conceivable that the thin cuticle of insect is injured readily by them. The abrasion theory on the mechanism of lethal effect of the so-called chemically inert pulverized materials which was advocated as a new theory by Alexander et al[1]., Parkin[21] etc. and was retested and proved by Beament[2], Kalmus[15] and

Wigglesworth[29,30,31] may also be applied to the explanation of the result of the present investigation.

Table 4. Characteristics of time-mortality regression line of adults of the azuki bean weevil, *Callosobruchus chinensis* L., treated with carborundum powders of various degrees of fineness.

Relative humidity (%)		73			91			100		
Sex	Degree of fineness	Regression coefficient b	Standard deviation σ	Median lethal time T(day)	Regression coefficient b	Standard deviation σ	Median lethal time T(day)	Regression coefficient b	Standard deviation σ	Median lethal time T(day)
Female	# 240	0.544	1.839	7.22	0.538	1.858	8.31	0.589	1.698	8.28
	# 320	0.625	1.600	7.38	0.499	2.003	8.17	0.681	1.469	8.10
	# 500	0.617	1.621	6.51	0.584	1.713	7.56	0.530	1.886	7.49
	# 700	0.478	2.093	6.42	0.542	1.847	6.75	0.630	1.588	6.81
	#1000	0.530	1.886	6.09	0.573	1.744	6.20	0.897	1.115	6.17
	#1500	0.580	1.725	5.38	0.895	1.117	5.58	0.622	1.610	5.68
	#2000	0.720	1.388	4.92	0.718	1.393	5.31	0.672	1.488	5.00
	#3000	0.885	1.130	4.64	0.764	1.310	4.72	0.737	1.357	4.32
	Control	0.483	2.072	6.82	0.553	1.810	8.30	0.408	2.454	7.17
Male	# 240	0.591	1.692	5.46	0.509	1.965	7.20	0.501	1.995	7.52
	# 320	0.507	1.971	5.42	0.513	1.950	6.32	0.523	1.913	6.88
	# 500	0.676	1.478	5.01	0.585	1.710	6.59	0.612	1.634	6.29
	# 700	0.613	1.631	4.86	0.626	1.598	5.83	0.493	2.028	5.50
	#1000	0.773	1.294	4.32	0.779	1.284	5.52	0.634	1.579	5.03
	#1500	0.865	1.157	3.54	0.829	1.206	4.59	0.643	1.556	4.51
	#2000	0.664	1.506	3.74	0.771	1.298	4.44	0.625	1.601	4.44
	#3000	0.668	1.496	3.21	0.967	1.034	3.51	0.873	1.146	3.25
	Control	0.385	2.598	4.86	0.503	1.989	6.84	0.558	1.793	6.08

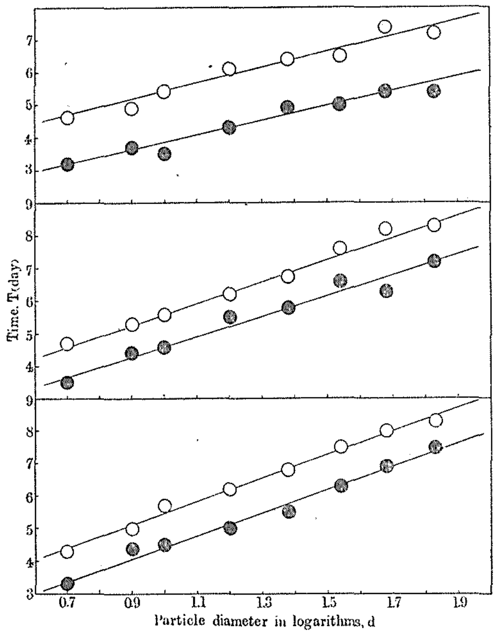

Fig. 4. Relation between time T and log particle diameter of carborundum powder d at the 50 per cent mortality of adults of the azuki bean weevil, *Callosobruchus chinensis* L. Solid line with hollow circles represents female, solid line with solid circles represents male. From top to bottom for 73, 91 and 100% relative humidity.

Hereupon, when we plot the logarithms of average diameter of particle d in table 2 against the median lethal time T in Table 4 an almost rectilinear relation as shown in Figure 4 is obtained. And the relationship seemes to be represented by the following equation :

$$T + b_2 d = a_2 ,$$

where, a_2 and b_2 are the parameters of the straight line. If the curve reqresenting the relation between the median lethal time and the logarithms of average diameter of particles is not rectilinear and is slightly curved, we must conceive a more enlarged formula with another quadratic term to express the relation of these two variables. It will do to apply the method of analysis of variance described by Bliss[5] for testing the linearity of relation of these two variables. The results of calculation are shown in Table 5. The ratioes of variance for the quadratic coefficient to that for the error 0.52 for female, and 0.49 for male in the case of 73% relative humidity ; 0.52 for female, 1.64 for male in 91%; and 1.08 for female and 0.08 for male in 100 %. As all these ratioes are less than 1.7 we can conclude that the relation between the median lethal time and the logarithms of average diameter of particle can be represented by the equation $T + b_2 d = a_2$, at least in the range of the average diameter from 67μ to 5μ. The results of calculation are shown in Table 6.

Table 5. Analysis of variance for testing lineality of relation between time T and log particle diameter of carborundum powder d at the 50 per cent mortality of adults of the azuki been weevil, *Callosobruchus chinensis* L., for the data in Table 3.

Relative humidity (%)			73		91		100	
Sex	Variance due to	Degrees of freedom	Sum of squares	Mean square	Sum of squares	Mean square	Sum of squares	Mean square
Female	Rectilinear relation between T and d, the linear term	1	6.92554	6.92554	12.59236	12.59236	14.42958	14.42958
	Single curvature from straight line, the quadratic term	1	0.02516	0.02516	0.01333	0.01333	0.02249	0.02249
	Error	5	0.24331	0.04866	0.12851	0.02570	0.10428	0.02086
	Total	7	7.19315	—	12.73420	—	14.55636	—
Male	Rectilinear relation between T and d, the linear term	1	4.99724	4.99724	10.40115	10.40115	13.70358	13.70358
	Single curvature from straight line, the quadratic term	1	0.01878	0.01878	0.09589	0.09589	0.00408	0.00408
	Error	5	0.19056	0.03811	0.29319	0.05863	0.27164	0.05433
	Total	7	5.20658	—	10.79023	—	13.97930	—

Table 6. Relation between time T and log particle diameter d at the 50 per cent mortality of adults of the azuki bean weevil, *Callosobruchus chinensis* L., for carborundum powder.

Relative humidity (%)	Sex	Regression equation $T+b_2d=a_2$	Precision of parameters a_2 and b_2		
			S^2	$V(a_2)$ at $\bar{d}=1.2775$	$V(b_2)$
73	Female	$T-2.509d=2.865$	0.044600	0.005575	0.040534
	Male	$T-2.131d=1.713$	0.034890	0.004361	0.031709
91	Female	$T-3.383d=2.254$	0.023640	0.002955	0.021484
	Male	$T-3.075d=1.574$	0.064847	0.008106	0.058932
100	Female	$T-3.621d=1.855$	0.021129	0.002641	0.019202
	Male	$T-3.529d=0.919$	0.045953	0.005744	0.041763

Here, we wish to propose an explanation as to why finer particles have larger lethal effect upon insect than coarser particles and also why the lethal time is distributed rectilinearly against the logarithms of particle diameter. Now, if we assume that the particle is a pin with both ends pointed and that only its two ends produce an lethal effect on insect and also that the length of the pin represents the particle diameter, we are able to explain the existence of the relation mentioned above in the following manner. When we divide the pin cross-wise into two, we shall get four ends each of which has a lethal effect. Furthermore, when we quarter it, we shall have eight ends. In other words, the number of ends increases in a geometrical progression. If we suppose that this end corresponds to a dosage, the relation of the number of pins' pointed ends to the mean lethal time, $T+b_2d=a_2$, is exactly alike to the relation of the time-dosage isomorts and it may be expected that the rectilinear relation should exist between time and particle diameter. From this statistico-physiological consideration, we shall be able to conceive that the crystalline edges of inert pulverized materials act upon the thin coating of wax layer of the insect cuticle which normally renders the cuticle impermeable to water, and that as a result of this abrasion the body water is lost and the insect is killed secondary by desiccation.

If we could ascertain that the particle diameter-mortality regression isochrons derived from the results of Table 3 shows the theoretical relations statistically, we shall be able to make another proof for the abrasion theory mentioned above. As an example, we have tried a calculation[3] of particle diameter-mortality regression isochrons from the experimental result obtained at the 91 % relative humidity. The result of the calculation are shown in Table 7. From the figures of χ^2-test, it may be concluded that the cumulated per cent mortality in probits shows the rectilinear relation to the logarithms of particle diameter excepting the data obtained at fifth

Table 7. Characteristics of particle diameter-mortality regression isochrons of adults of the azuki bean weevil, *Callosobruchus chinensis* L., for carborundum powder. Calculated from the data of Table 3 obtained under the condition of 91 % relative humidity.

Sex	Time T(day)	Regression coefficient b	Standard deviation σ	Log median lethal particle diameter d	Median lethal particle diameter $D(\mu)$	Degrees of freedom n	Probability in χ^2 test P_r
Female	2	-0.650	-1.539	-2.44211	0.0038	5	0.91
	3	-0.794	-1.259	-1.32060	0.0478	6	0.98
	4	-1.332	-0.751	0.12797	1.3427	6	0.53
	5	-1.990	-0.503	0.82237	6.6431	6	0.29
	6	-2.261	-0.442	1.16317	14.561	6	0.92
	7	-2.360	-0.424	1.43250	27.071	6	0.08
	8	-2.299	-0.435	1.69439	49.475	6	0.41
	9	-2.308	-0.433	1.93581	86.260	5	0.88
	10	-2.226	-0.449	2.18766	154.05	3	0.74
	11	-1.938	-0.516	2.53186	340.30	3	0.72
	12	-1.603	-0.624	3.01018	1023.7	2	0.54
Male	2	-0.582	-1.719	-2.36192	0.0044	6	0.99
	3	-0.805	-1.242	-0.58973	0.2572	6	0.25
	4	-1.853	-0.540	0.80550	6.3899	6	0.11
	5	-2.176	-0.460	1.17002	14.792	6	<0.05
	6	-2.090	-0.479	1.49380	31.174	6	0.05
	7	-2.004	-0.499	1.76904	58.754	6	<0.05
	8	-1.950	-0.513	2.07075	117.69	5	0.06
	9	-2.456	-0.407	2.20143	159.01	3	0.52
	10	-2.429	-0.412	2.43314	171.11	2	0.97
	11	-3.329	-0.300	2.39385	247.66	1	0.47

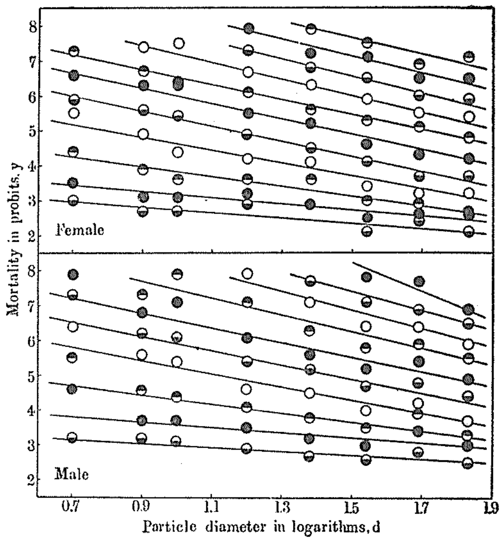

Fig. 5. Particle diameter-mortality regression isochrons of adults of the azuki bean weevil, *Callsobruchus chinensis* L., for carborundum powder under the condition of 91 % relative humidity. From bottom to top 2, 3, 4, 5 ....12 days.

and seventh day in male. In this case, we can consider that the particle diameter of carborundum powder is quite the same as the concentration in toxicant. These relations are shown in Figure 5.

Briscoe[6] showed that the particles of carborundum and quartz powder over 15μ in diameter are too large to have a lethal effect on the granary weevil, that the effectiveness increases inversely with reduction in particle diameter from 10μ to 1μ, and that there seems to be a maximum of effectiveness at about 1~2μ. Further he pointed out that the adhesion of dust to insects appears to be very important, that the particles above 15 μ do not adhere at all, that the particle of about 5 μ adhere better to wheat and weevils, and also that the particles of about 1 μ adhere best. Maximum adhesion at about 1 μ agrees very well with the fact that the maximum effectiveness was found at about 1~2μ. Using the same samples of carborundum powder as those used by the writer, viz., #280, #500, #1000, #1500 and #3000 degrees of fineness, Yasue[34] carried out experiments and found a definite correlation between the duration of life of the small rice weevil and the particle diameter of carborundum powder. He reported that shorter durations of life were obtained with smaller particles and that the extra fine powder #3000 was most effective upon the weevil.

The fact that the finer the particles the more effective they are upon insects, has also been reported on some other inert dusts. Chiu[7] described the result of experiments in which four degrees of fineness of powder of crystalline silica were used against the bean weevil, *Acanthoscelides obtectus* (Say), and reported that the relative effectiveness increased as the particle diameter decreased, the powder over 100μ possessing no lethal effect upon weevil, and also that the adhesive quantities of powder to insect affect the rate of effectiveness. Chiu[7] carried out experiment using also the rice weevil and the granary weevil. According to his conclusion, the fineness of powder is a very important factor in producing the lethal effect upon weevil: the finer the particle the more lethal effect it has upon weevils in some range of particle diameters, and when particle diameter is over 37μ it loses the effectivenss in practical uses. David and Gardiner[8] reported that the granary weevils were killed more rapidly by the finer grades of talc and slate powder than by coaser grades of them, and also that the fine particles of carborundum powder gave the similar effect on the granary weevils and the lesser grain borer. Nagasawa and Uruha[18] also obtained a similar result in experiment with the azuki bean weevil using the Yamagata bentonite powders classified into three grades.

However, there are many cases where the increase of effectiveness of inert dusts to insects are not brought by the decrease of particle diameter. According to Parkin,[21] the most effective particles in felsper, dolomite, flint etc. to the insects of stored grain are probably those smaller than 10μ in diameter, and the concentration of this fraction may be of greater importance than that of the powder as a whole; namely, equal mortality is obtained by a low concentration of a fine powder and by a higher one of a coarser powder. And also in the experiment using the six sedimented fraction of quartz powder of which the approximate mean diameter were 0.5, 1.8, 3.2, 5.5, 10.0 and 15.0μ, he found that the most effective particle to the granary weevil at a concentration of 1 per cent by weight of grain was the fraction of about 1.8μ in mean diameter, and the effectiveness of particles larger than 30μ was almost negligible. And he stated that the smaller effectiveness observed in finer particles than those of 1.8μ in diameter is due to change in shape or surface of particles by long period of grinding. Germer[11] tested the lethal effect of quartz powder ground to three different grades, viz., from colloidal size to 150μ, from colloidal size to 12μ, and from colloidal size to 5μ using the granary weevils. And he states, though the powder of the coarsest grade showed the lowest mortality, this difference is not significant from the practical point of view because the colloidal particles from the lumps that failed to adhere to weevils and its effectiveness decreaaes.

It should be considered usual that the finer particles adhere readily to the objects than the coarser particles as described in the papers of Alexander et al[1]., David and Gardiner[8], Fitzgibbon[9], Smith and Goodhue[25], Streeter and Pankin[26] Wilcoxon and McCallan[33]. By the weighing method of measuring adherence, David and Gardiner[8] demonstrated that a greater quantity of fine carborundum powder adheres to insects than coarser carborundum powder and that this relationship holds true for both smooth and hairy insects. Heuberger[13], however, pointed out that the fungicide particles of below about 2μ in diameter become more difficult to adhere and he presumed it to be due to a marked tendency of such powders to form aggregates.

As described above, the writer proved the appropriateness of the abrasion theory on the lethal effect of inert pulverized materials upon insects from the statistico-physiological point of view. But many cases of lethal effect of inert dusts which cannot be explained by the theory also occurred among many experiments using other inert pulverized materials. In facts, as described in the papers of Mote et al,[16] Richardson and Glover[22], Shafer[24] and Wilcox[32], the inert dusts worthless as a food is taken into the digestive tracts consciously or accidentally in the course of cleaning of anntennae, legs and elytra. And the death results possibly from the blockade of digestive tract by these inert dusts. David and Gardiner[8] observed that the several dyes, carborundum powder and lamp soot were eaten by the red flour beetle and others. On the other hand, we must consider furthermore the problem of suffocation, namely the inert dusts will enter the spiracles and contribute to the lethal action, though some negative facts were presented by Hockenyos[14], Chiu[7], Alexander et al[1]., David and Gardiner[8]. Observationon the intrusion of dust particles into spiracles were made also by Hamilton[12], Webb[28], Roy and Gohsh[23], David and Gardiner[8] etc.

SUMMARY

It has already been demonstrated that the carborundum powder has a lethal effect upon some insects of stored grain under certain conditions and that finer particles are more effective than coarser ones. The writer investigated this problem from the statistico-physiological point of view, and presented a proof of the abrasion theory for the mechanism of lethal effect of the so-called chemically "inert" pulverized materials upon insect advanced by Alexander et al[1]., Parkin[21], Wigglesworth[29,30,31] and others. According to this theory, the impermeability of insect cuticle to water is broken by the abrasion made by inert dusts and the death is caused by the rapid loss of body water. The main points of the present investigation are as follows :

(1) By dusting method the lethal effect of carborundum powder of eight different degrees of fineness upon adults of the azuki bean weevil, *Callosobruchus chinensis* L., has been investigated under the constant conditions of 30°C and relative humidities of 73, 91 and 100 %.

(2) For all particle diameters, the time-mortality curve proved to be more linear when the net percentages of mortality in probits were plotted against the time of survival after treatment than when they were plotted against the logarithms of time.

(3) In both females and males, a definite lethal effect of carborundum powder was recognized in all particle diameters when the survival times of treated lots were compared with that of untreated lot.

(4) Fine particles of carborundum powder have more larger lethal effect upon weevils than coarser ones and the lethal times are distributed rectilinearly against the logarithms of particle diameters.

(5) If we assume that the particle is a pin with both ends pointed and that only its two ends produce a lethal effect on insect and also that the length of a pin represents the diameter of a particle, we are able to explain the existence of the relation mentioned above in the following manner. When we divided the pin crosswise into two, we shall get four ends, each of which has lethal effect. Furthermore, when we quarter it, we shall have eight ends. In other words, the numbers of end increases in a geometrical progression. If we suppose that an end of a pin represents a dosage, the rectilinear relation mentioned above is exactly alike the time-dosage isomorts relation.

(6) From this statistico-physiological consideration, we shall be able to infer that the crystalline edges of inert dusts act upon the thin coating of wax layer of the insect cuticle which is normally impermeable to water, and that as a result of this abrasion the body water is lost and that the insect is killed secondary by

desiccation.

(7) The abrasion theory may be said to have been given another proof theoretically from the result of calculation of particle diameter-mortality isochrons derived from the time-mortality data.

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