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Recent Trends in Performance Test Methods for Transport Packages and Application to Fresh Produce

Takeo SHIINA *

Abstract

The functions of packaging include protection, containment, information, utility of use, and promotion. It is important in designing packaging to provide these functions with reduced cost and environmental loads. Performance tests of packaging can help realize it.

Performance test methods for transport packages are summarized based on current Japanese Industrial Standards (JIS Z 0200: 2023), which corresponds to the ISO 4180-2019. This test method is widely used for transport packages within the distribution system to ascertain their performance against hazards. Hazards include shock, vibration, stacking stress, low pressure, temperature and humidity, wetness, and dewing. There are many related test methods to be employed for each hazard.

In the case of fresh fruits and vegetables, special considerations are required to conduct performance tests depending on their unique characteristics. Research on several topics was presented, including 1) damage by repetitive shock (shock fatigue failure), 2) damage to the peach fruits that ripen after harvest, and 3) shock pulse analysis of the outer package for produce in the drop test.

Performance Test Methods for Transport Packages

Performance test methods are widely used for transport packages within the distribution system to ascertain their performance against hazards. There are several test standards for the performance test, including ISO 4180, ASTM D4169, JIS Z 0200, etc. It is recommended that national standards be harmonized with corresponding international standards. A revision of JIS Z 0200 (2023) was established in 2023 based on its correspondence, ISO 4180-2019 (revised version of ISO 4180-2009). Japan Packaging Institute (JPI), the secretariat of ISO/TC 122, and Japanese experts have actively worked on revising both ISO 4180-2009 and ISO 4180-2019. In the previous revision of JIS Z 0200 (2020), the structure of this standard was unusual to make it possible to include the principles of ISO 4180-2009 and to avoid over-packaging (ISO was included in Annex A as normative in JIS). After revising the ISO 4180 with the leadership of Japanese experts, it became possible to harmonize JIS Z 0200 to ISO 4180-2019 as MOD (some differences will be proposed for future revision of ISO).

The scope of the JIS Z 0200: 2023 is "This standard specifies test methods for evaluating whether the packaging is adequately protected against vibration, shock, and compression that packaged goods are subjected to during distribution. Packaged goods that are subject to the Fire Service Act and other related laws and regulations are excluded.”

* Prof. Dr , Graduate School of Horticulture, Chiba University (Matsudo 648, Matsudo, Chiba 271-8510, Japan)
TEL:047-308-8847, FAX:047-308-8847, Email: shiina@chiba-u.jp

The documents (JIS C 60068-1, JIS Z 0108, JIS Z 0179, JIS Z 0201, JIS Z 0202, JIS Z 0203, JIS Z 0205, JIS Z 0212, JIS Z 0217, JIS Z 0232, ISO 2234, ISO 2873, ISO 7965-2) are referred to in the text in such a way that some or all of their contents constitutes requirements of this document, thus Normative references.

Typical hazards in the logistics process, and the related international standards and JIS standards are shown in Table 1 (Shiina, 2024).

Table 1 Expected hazard during the logistics process, and related standards

Basic factor in logistics	Hazard	Related test standards		
		Type of the test	ISO	JIS
Transport	--- Vibration during transportation --- Repetitive impact by bouncing	Vertical random vibration test	13355	Z 0232
		Sinuloidal vibration tests using a variable frequency	8318	Z 0232
		Vibration tests at fixed low frequency	2247	ISO 2247
	Horizontal impact by sudden stot or start	Horizontal impact test	2244	Z 0205
	Horizontal impact by linking work of rail-way freiht car			
	Stacking stress during transportation	Random vibration test	13355	Z 0232
		Sinuloidal vibration tests using a variable frequency	8318	
	Low pressure by high altitude	Low pressure test	2873	ISO 2873
Handling	Drop impact by manual handling	Vertical impact test by dropping	2248	Z 0202
	Drop impact by mechanical handling		EN 14149	EN 14149
	Horizontal impact during handling by forklift or crane as such	Horizontal impact test	2244	Z 0205
	Rough handling by rolling	Rolling test	2876	ISO 2876
	Topple	Toppling test	8768	ISO 8768
	Handling of unit load	Stability testing of unit loads	10531	Z 0170
Storage	Compression load in stacking storage in warehouse	Stacking tests using static load	2234	ISO 2234
		Compression and stacking tests using a compression tester	12048	Z 0212
Climate	Temperature and humidity	Hight temperature test	2233 IEC 60068-1	Z 0203 C 60068-1
		Hight temperature/High humidity test		
		Low temperature test		
	Wet, dewing	Water-spray test	2875	Z 0216

An example of the performance test schedule based on certain distribution hazards is shown in Table 2. It is allowed to use multiple test specimens to save testing time and to avoid over-packaging since the probability of the occurrence of the highest levels of different hazards in the same distribution process may be low.

The test levels are chosen depending on the kinds of hazards and their levels during the distribution process considered. For example, in the random vibration test, the total test time is 120, 60, and 30 m depending on the transport distances of 4,000, 2,000, and 1,000 km, respectively. There are 2 kinds of PSD, Profile A (Grms is 2.97 m/s^2) and Profile B (Grms is 5.926 m/s^2). A random vibration test using Profile

A precedes the test using Profile B. The testing time ratio of Profile A and B is 5:1, except for the case where shipping orientation cannot be predicted. Another time ratio occurs because the test is for three different placements of the specimen and the minimum test time is 5 m.

Table 2 Example of performance test schedule based on certain distribution hazards

Test schedule	Experimental test order			
	1	2	3	4
A: Sequential test using one specimen	Conditioning	Compression test	Vertical random vibration	Free fall test
B: Parallel test using multiple specimens (in the case of four specimens)	Conditioning	Vertical random vibration	Random vibration test in rough road transportation	Free fall test
	Conditioning	Compression test		
	Conditioning	Temperature and humidity environmental test		
	Conditioning	Low pressure test		

Application to Fresh Produce

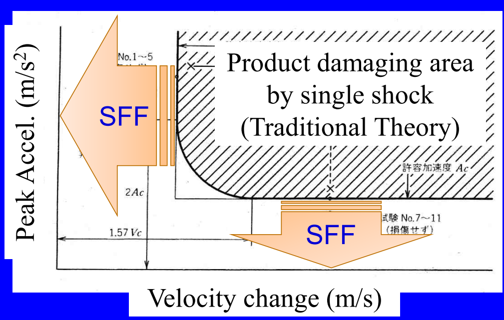
World Resources Institute (WRI) released “Global Food Loss and Waste Accounting and Reporting Standard (Ver. 1.0)” in 2016 and “The Global Benefits of Reducing Food Loss and Waste, and How to Do It” in 2023. It was illustrated that food loss of fresh fruits and vegetables is high among the food products in the former. It is stated that “Reducing food loss and waste generates benefits for economies, for businesses and consumers, for human health, and for the environment.” in the latter.

Based on such a situation and my expertise, some of the recent research topics are presented here. Topics include 1) damage by repetitive shock (shock fatigue failure, SFF), 2) damage by shock and vibration to the peach (*Prunus persica* (L.) Batsch) fruits that ripen after harvest, and 3) shock pulse analysis of the outer package for produce in the drop test.

1) Damage by repetitive shock

The S-N (stress versus the number of cycles to failure) curve is widely used in the packaging performance test on vibration damage. On the other hand, in the packaging performance test for shock damage, it is generally considered that the damage boundary curve (DBC) is used. DBC is the curve showing the threshold level for both velocity change (m s^{-1}) and peak acceleration (m s^{-2}) where the product gets unacceptable damage by a single shock. Kitazawa et al.

Fig.1 Repetitive Shock Below the Threshold Level Causes Fatigue Damage to the Products

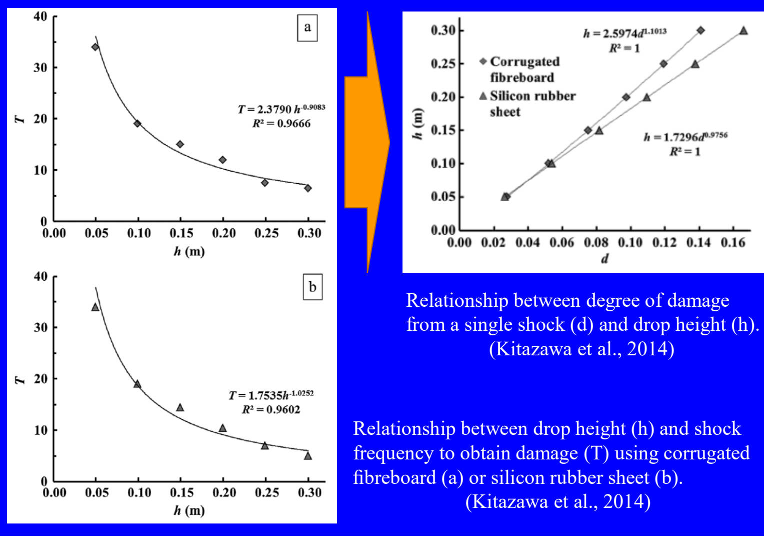


(2014) reported the shock fatigue failure (SFF) of fresh produce by repeated shocks, which had lower values than the threshold values of the single shock in the DBC (Fig. 1).

To implement the SFF concept in the supply chain, it is necessary to develop a database on the SFF of produce and to collect shock data (vibration acceleration data) during transportation. Therefore, we propose a method to facilitate this concept by using the database on the SFF of the produce and the acquisition and analysis of the vibration data in the supply chain. The database development and data analyses will be conducted on the WAGRI-DEV system (WAGRI is a public cloud service that provides data and programs useful for agriculture, such as weather, farmland, and yield forecasts).

Fig.2 shows an example of the SFF data. Fig.3 shows the measured shock data during mango transportation. In the case of mango fruits, it was possible to estimate the cumulative degree of damage (0.76<1.0) after transportation. It allows us to ensure the mango quality based on the SSF data and environmental data during transportation. A program for acceleration peak extraction that works on the WAGRI-DEV will provide the quality assurance system for S&V.

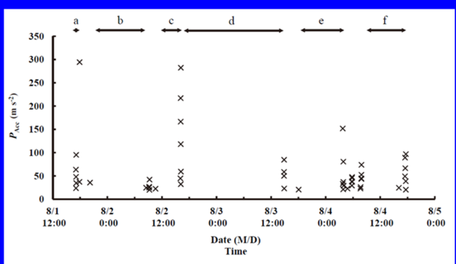
Fig.2 Example on the Strawberry Fruits



Relationship between degree of damage from a single shock (d) and drop height (h). (Kitazawa et al., 2014)

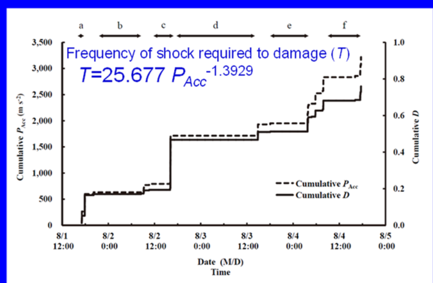
Relationship between drop height (h) and shock frequency to obtain damage (T) using corrugated fibreboard (a) or silicon rubber sheet (b). (Kitazawa et al., 2014)

Fig.3 Shock frequency and shock level during mango transport from Amami-Oshima to Tsukuba



(Nakanishi et al., 2015)

Fig.4 Cumulative value of peak acceleration (P_{Acc}) and degree of damage (D) during mango transportation :simulation



(Nakanishi et al., 2015)

2) amage by shock and vibration to the peaches affected by storage conditions

In our previous study (Nakamura et al., 2021a), we reported a mathematical model of the fruit firmness characteristics based on the cumulative respiration of the peach fruits under different storage temperature conditions. Furthermore, we have reported the shock damage characteristics of peach fruit with different firmness values (Firmness Index, *FI*) (Nakamura et al., 2021b). Based on these studies, we have carried out research on the development of an estimation model for damage characteristics of peach fruit by repetitive shock experiencing different temperature profiles before shipping to the consuming area (Nakamura et al., 2023).

A constant temperature at 20 °C (Profile-1, hereafter P-1) and changing temperatures (P-2, P-3A, and P-3B) were set as shown in Fig. 5. Each profile has an average temperature of 20 °C. P-1 and P-2 are 7-day storage, whereas P-3A and P-3B are 3-day storage. P-3A and P-3B were set for shipping the peach fruit to the consuming area with a longer transport distance that peach fruit are required to have more tolerability against repetitive shock.

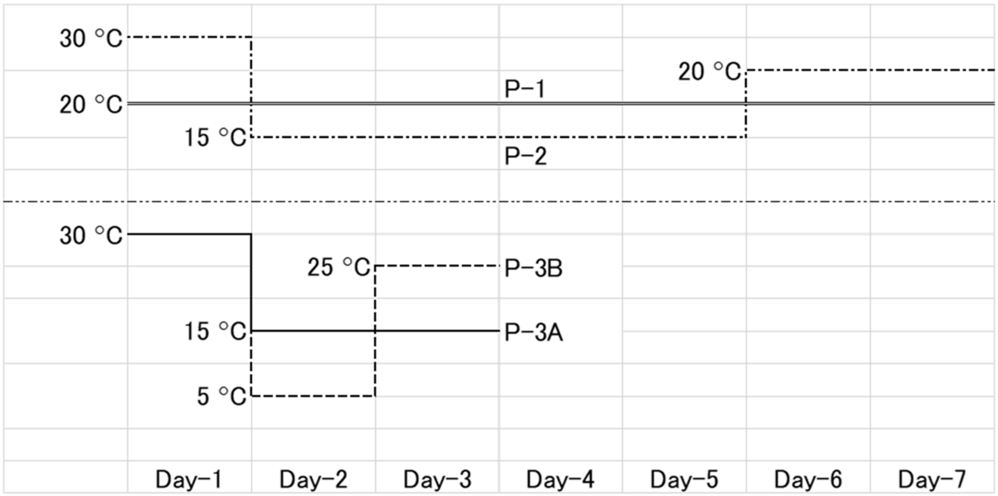


Figure 5 Temperature profiles (P-1, P-2, P-3A, and P-3B) of the storage

The effect of the temperature (T (°C)) on the respiration rate (*Resp*) of peach fruits was obtained as shown in Equation 1.

$$Resp = 5.38\times10^{13}\exp(-8201\text{x}(1/T)) \qquad (1)$$

Fig. 6 shows the results of cumulative respiration at different temperature profiles (shown in Fig. 5). After 72 hours, cumulative respiration of P-3A and P-3B were 3429 and 3968, respectively. After 168 hours, cumulative respiration of P-1 and P-2 were 6405 and 7480, respectively.

The values of *FI* of peach fruits after storage under different temperature profiles were calculated by using cumulative respiration. Based on the *S-N* curve parameters, α and β, and *FI* values, the estimated number of shocks required to lose the commercial value of peach fruit after different storage temperature profiles were shown in Table 3.

The number of shocks required to lose the commercial value of peach fruit is different depending on the temperature profiles. Peach fruit that experienced 7-day storage (P-1 and P-2) have less than 4 times of shock under the peak acceleration of 90 (G) and around 10 times under 50 (G). On the other hand, peaches experienced 3-day storage (P-3A and P-3B) more than 20 times under 50 (G), suggesting the capability of transportation to double distance compared with the peaches under profiles P-1 and P-2.

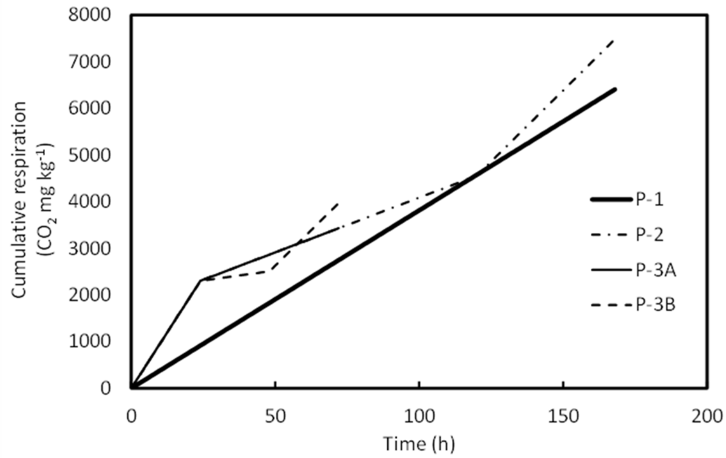


Figure 6 Cumulative respiration of peach fruits under different temperature profiles.

Table 3 The estimated number of shocks required to lose the commercial value of peach fruit at different temperature profiles assumed.

Temperature Profile	Estimated FI	Estimated number of shock to lose the commercial value			
		Peak acceleration of the shock (m s^{-2}) or G value (G)			
		49 (5)	196 (10)	490 (50)	882 (90)
P-1	1.31	745.8	58.6	10.9	3.7
P-2	1.25	625.6	50.9	9.7	3.3
P-3A	1.99	3228.4	185.1	28.0	8.3
P-3B	1.77	2146.9	135.2	21.7	6.7

3) Shock pulse analysis

Shock and vibration are important hazards in handling and transport that cause physical damage to products or their packages. For the analysis of transport vibration, Nyquist frequency is widely used as an indicator for selecting measurement frequency or sampling rate. However, little is known about the analysis method of the shock pulse in the physical distribution. Shiina et al. (2022) analyzed the shock pulse inside the outer package for fresh produce and showed a very short duration of time (ca. 2 ms) for the shock pulse. It was much shorter than commonly used for the shock test and a sampling time of small data logger in the market. Therefore, we have proposed a method that effectively obtains the optimal sampling interval in terms of peak acceleration (*PAcc*) and velocity change (*VC*) (Kotobuki et al., 2024). The summary of this research is shown here.

Three types of shock pulses were generated to test the efficiency of the analysis method. Fig. 7 shows generated pulses of half-sine, triangular, and a combination of half-sine and triangular. For each shock pulse, we calculated the expected relative value (*ERV*) of *PAcc* and *VC* for each sampling interval against the original values.

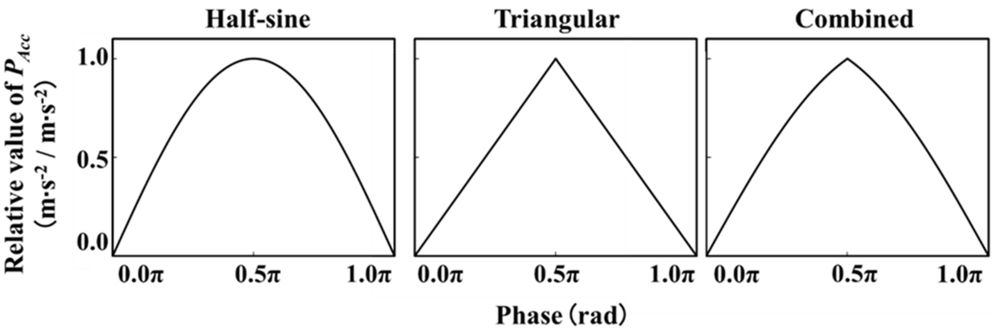


Figure 7 Three types of shock pulse used for the analysis.

Fig. 8 shows a relationship between the sampling interval and *ERV* of *PAcc* for different types of shock pulse. The longer the sampling interval, the lower the *ERV* was found regardless of the type of shock pulse. The sampling interval to obtain 90 % of the original value was 50 % of the pulse duration for half-sine, 20 % of the pulse duration for triangular, and 32 % of the pulse duration for half-sine and triangular combined. Therefore, we concluded the optimal sampling interval for *PAcc* measurement was 20 % of the pulse duration.

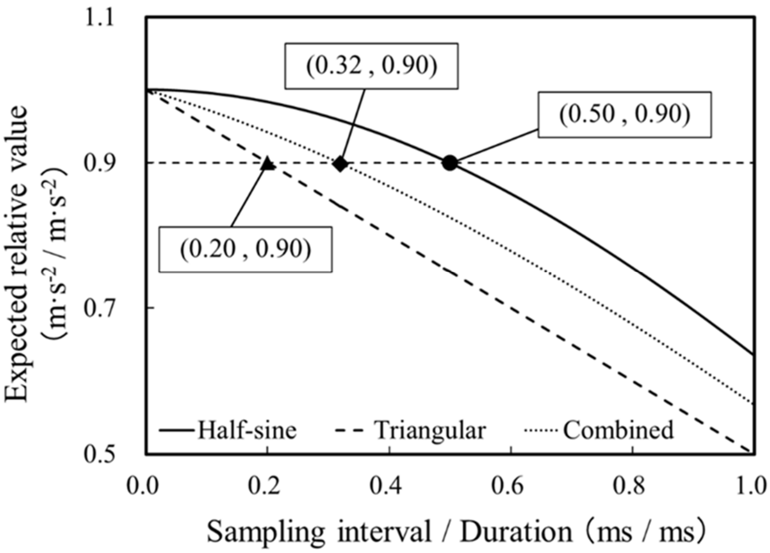


Figure 8 Relationship between sampling interval and expected value of PAcc

Fig. 9 shows a relationship between the sampling interval and *ERV* of *VC*. The longer the sampling interval, the lower the *ERV* was found regardless of the type of shock pulse. The sampling interval to obtain 90 % of the original value was 30 % of the pulse duration for half-sine, 32 % of the pulse duration for triangular, and 31 % of the pulse duration for half-sine and triangular combined. Therefore, we concluded the optimal sampling interval for *PAcc* measurement was 30 % of the pulse duration.

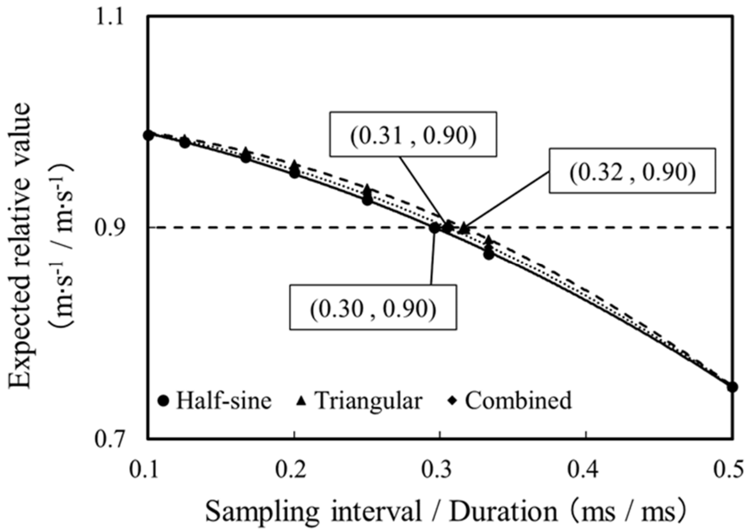


Figure 9 Relationship between sampling interval and expected value of VC.

Based on the results obtained, it was concluded that the optimal sampling interval was 20 % of the pulse duration. If the time duration of the shock pulse is 2 ms, then the required sampling time is 0.4 ms. These results help to reconsider/design the sampling interval of a simple shock logger and to optimize shock measurement in the physical distribution of postharvest products.

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