The History and Application Examples of Portable FWD in Japan

1. History of Portable FWD

The history of FWD and portable FWD (PFWD) is shown in Table-1. Basically, PFWD developed in Japan consists of 2 different types. The origin of one type was developed in 1957 by S. Asai, to measure the strength of base course and subgrade[1]. As shown in Fig.-1, it the 12kg falling weight loading plate and measure the displacement of the ground with guide stick and this evaluates as impact value (cm).

Table-1 History of FWD and PFWD

Year	Country	Name	Overview
1955	USA	Benkelman A. C.	The development of Benkelman beam
1955	USA	Hveem, et al.	Deflection measurement by the moving wheel using the underground laid differential transducer.
1956	Japan	Mr. Arai, et al.	Asai developed an impact type plate loading test and he proposed an evaluation method by the Impact Value.
1964	Denmark	National Road Laboratory	The falling weight type deflectometer was developed and an pit testing was implemented.
1966	Denmark	Scrivner, et al.	Dynatest by the sine wave of 8 Hz is developed in 4.5 kN of loads.
1972	Denmark	Bohn, et al.	By integrating velocity, the measurement of the deflection at the pavement becomes possible.
1974	Denmark	Phoenix A/S	Change a cone spring into the rubber buffer and Phønix begin the sale of the FWD.
1976	Denmark	Dynatest A/S	Dynatest begins manufacture and sale in the FWD, too.
1976	Sweden	KUAB	KUAB is the development of the 2 mass system FWD.
1982	Denmark	Phoenix A/S	The automaticallying control of the system and the deflection measurement by the PC.
1983	Japan	Ministry of Transport, harbor Institute of Technology, Prof. Kasahara, Hokkaido Institute of Technology.	The first time, Phønix FWD's being introduced into Japan.
1986	Japan	Prof. Maruyama, et al.	It was begun research by 2 mass system FWD .
1987	USA	FHWA	An exploratory committee about the measurement of the FWD was installed in the SHRP.
1988	Netherland	CROW	An exploratory committee about the FWD was organized.
1990	Japan	FWD Research is started	I began a research about the use of the FWD.
1991	Japan	Prof. Kasahara, et al.	The development of the handy Falling Weight Deflectometer.

Another flow is the equipment which was made an FWD prototype and measures the load and the deflction which occurs to the loading plate, falling in the falling weight with the hand guide. It was developed from cooperative project in Denmark in 1964, then commercialized by Phoenix A/S（current Carl Bro Pavement Consultants）in 1976 which falls weight by manual hydraulic pump and measure displacement by integration of measured value from velocity meter[2].

FWD is first introduced in Japan in 1983. The first domestic PFWD was developed in 1991 and published in the paper "Development of portable FWD" by Prof. A. Kasahara et al. at 19th Japan Road Conference.[3] Since then, a number of study[4,5] and application examples of PFWD has been published, utilizing its easy transportation and operation. At present, 4 guidelines and standards for PFWD are published and its use is expanding.

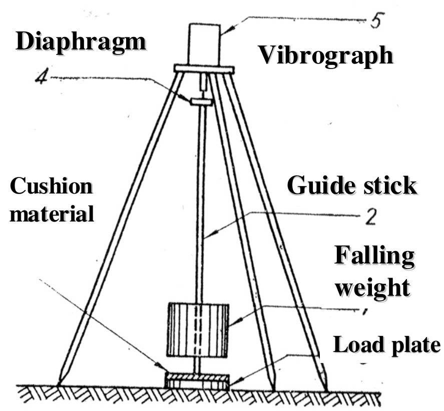


Fig.-1 Impact load test by Asai type

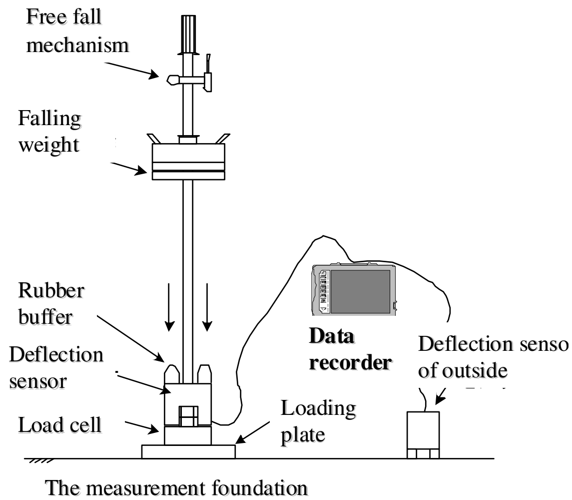


Fig.-2 Typical Structure of PFWD

2. PFWD used in Japan

The basic structure of PFWD in Japan has the weight which can be lifted by hand and the total weight of equipment is less than 30kg. Generally, the fall height of the falling weight for the necessary impact load to occur is equal to or less than 0.7 m. The rod guides for weight falling and slide seal is furnished to decrease friction. Also, fixable mechanism of weight falling is furnished to fix the weight stable at specified height. The half sine wave profile of impact load through rubber buffer shows gradual peak, it

Table-2 The specification of the portable FWD using Japan

Product name	Handy FWD	PRIMA 100	FWD Light	DPLT (ZFG2000)
Manufacturer	Freesia Macross Co., LTD.	Grontmij | Carl Bro Pavement Consultants	Tokyo Sokki Kenkyujo CO.,LTD.	Itec Invention (Seles marketing)
Rubber buffer	3 peaces (Op, 4,5)	3peaces (Op, 2, 4)	3 peaces (Op, 2, 4)	1peace (Belleville spring)
Falling weight (kg)	8 (Op. 3,10,15)	10 (Op. 15,20)	5 (Op. 10,15)	10
Impact load (kN)	～20	～20	～20	～10
Loading plate (mm)	90 (Op. 200,300)	100 (Op. 200,300)	100 (Op. 200,300)	300 (Op. 150)
Deflection sensor	Velocity meter	Velocity meter	Accelerometer	Accelerometer
Measurement item	Load, Deflection (Integrated Velocity)	Load, Deflection (Integrated Velocity)	Load, ACC, 0-Peak time, Time product, Deflection (Integrated ACC)	Load, ACC, 0-Peak time, Time product, Deflection (Integrated ACC)
Evaluated value	—	Esg	E0, Dynamic K value	E0, Dynamic K value
Ext. sensor num.	0, Op. position (1 peace)	0, Op. position (2 peace)	0, Op. position (2 peace)	0
Max. deflection (mm)	2	2.5	2.5	0.5, 5 (Range change)
Recorder	Data logger (Op. Note PC)	Note PC	Data logger, CF Card (Op. Note PC)	Data logger, CF Card
Storage data	Logger internal-memory	File	File	Print out, File

takes 7 - 15ms from the beginning of loading to the peak. Typical structure of PFWD is shown in Fig.-2.

PFWD used in Japan consists of 4 types; FWD-Light (Japan), HFWD (Japan), PRIMA100 (Denmark) and ZFG2000 (Germany). The specification of PFWD is shown in Table-2.

The number, shape, hardness of buffers are different in each type of PFWD, so load impact and loading time are different even they use same mass weight and falling height. However, the obtained deflection depends on loading energy, the difference in each types becomes small by examining modulus of subgrade reaction (K value) and Elastic modulus (E value). Other report indicates that almost same load impact can be obtained by using same shock absorbing buffer in different types.

3. Measurement of Base course & Subgrade

3.1 Purpose

Generally, the rigidity of natural/artificial subgrade is evaluated by plate loading test which calculates K value from the relation between load strength and displacement at static loading. In PFWD, loading and displacement are measured and obtains K value from its relation. K value evaluates the rigidity of the subgrade.

3.2 How to calculate K value

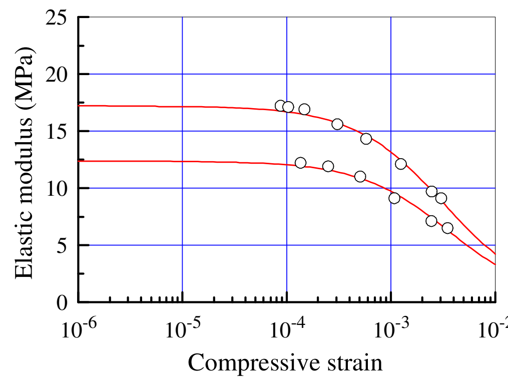


Fig.-3 Elastic modulus and compressive strain

If the diameter of loading plate in PFWD is less or more than 30cm, K value ($K_{P.FWD.\phi}$ value) is calculated by appropriate displacement from the diameter. ϕ indicates the diameter of loading plate, so $K_{P.FWD.10}$ means K value when using loading plate with 10cm diameter. K value is in inverse proportion to loading plate diameter, so the diameter is corrected and K value at 30cm diameter ($K_{P.FWD}$) is calculated.

3.3 Displacement at calculating K value

Deformation modulus of soil varies depends on the volume of strain (Fig.-3). Deformation modulus with 30cm diameter loading plate and 1.25mm displacement is nearly equivalent to 10^{-3} strain level (Plate loading test) according to the formula (1) by Bussinesq.

$$E = \frac{a\pi p\left(1-\nu^2\right)}{2\delta} \qquad (1)$$

where E : Elastic modulus on subgrade (MPa)

p : Contact pressure (kPa)

a : Diameter of loading plate (m)

ν : Poisson ratio of subgrade

δ : Deflection (mm)

When the diameter of loading plate is 10cm and displacement is 1.25mm, the strain level becomes 10^{-2}. Therefore, K value ($K_{P.FWD.\phi}$ value) is calculated with appropriate displacement for loading plate diameter, then, loading plate diameter is corrected and K value ($K_{P.FWD}$ value) at 30cm loading plate diameter is calculated. Thus, the measurement shall be conducted to obtain at least three different displacements including 0.417 in the middle, by changing weight mass and falling height. One of the displacements shall be near 0.417mm.

3.4 Measurement Method

The number of fall at one measurement point shall be 4 times or more. The reason is the measurement result at first fall varies due to unstable contact between loading plate and the ground. First fall is regarded as primary fall, so the load and displacement from the second fall are recorded as measurement data. The measurement location and intervals are designed depending on subgrade.

The procedure of PFWD measurement is as follows:

1) Remove the loose materials on subgrade surface and level it as possible. If the subgrade is crushed stone or it is difficult to smooth the surface, use sand cushion.
2) Place PFWD at measurement point on the subgrade.
3) Free-fall the weight from specified height, then measure the generated maximum load and maximum displacement at the center of the load.
4) Measure at 3 or more different height at one measurement point.
5) Fall the weight from lower height in order.
6) Fall the weight 4 or more times from the same height.

PFWD can evaluate various objects as subgrade or pavement. However, displacement becomes considerably small if the strength of object is high. It is desirable to

Diameter of loading plate	D0 at K value
9cm	0.375mm
10cm	0.417mm
20cm	0.833mm

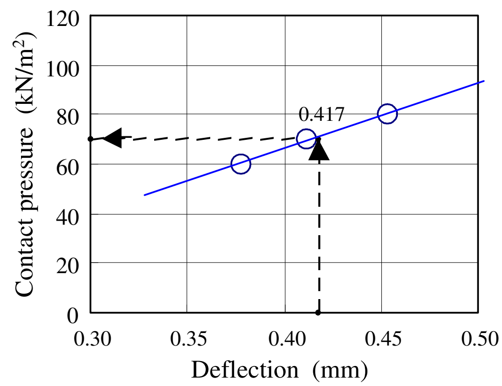


Fig.-4 Displacement and load at one measurement point measure with changing the loading plate.

3.5 Data processing

Average the measured load and displacement at every falling height, then calculate $K_{P.FWD}$ value from loading stress and displacement using formula (2) and (3).

$$K_{P.FWD.\phi} = (P_{P.FWD.\phi} / \delta_{P.FWD.\phi}) \quad (MN/m^3) \quad (2)$$

$$K_{P.FWD} = K_{P.FWD.\phi} \cdot \phi_{P.FWD.\phi} / \phi_{PLT} \quad (MN/m^3) \quad (3)$$

where $K_{P.FWD.\phi}$: K value at loading plate diameter ϕ

$P_{P.FWD.\phi}$: Contact pressure when displacement is $\delta_{P.FWD.\phi}$

$\delta_{P.FWD.\phi}$: displacement

$K_{P.FWD}$: K value equivalent to 30cm diameter loading plate

$\phi_{P.FWD.\phi}$: loading plate diameter of PFWD

ϕ_{PLT} : Basic loading plate diameter (30cm)

3.6 Evaluation of data

Convert the obtained $K_{P.FWD}$ value to K_{30} value, judge the rigidity of subgrade. Plate loading test uses static load and PFWD uses impact load, so $K_{P.FWD}$ value and K_{30} value do not exactly correspond. If the subgrade is sand or gravel, $K_{P.FWD}$ value is larger than K_{30} value. Therefore, it is required to evaluate subgrade considering the above. The relationship between $K_{P.FWD}$ value and K_{30} value is shown in formula (4).

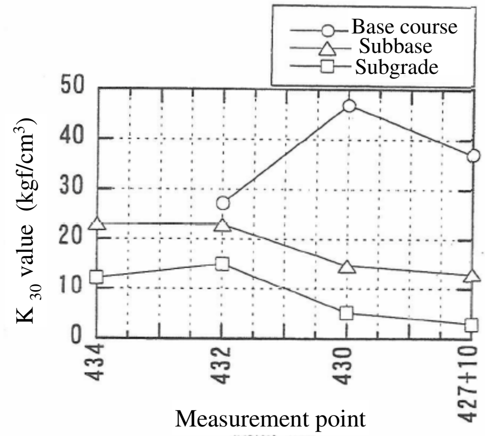


Fig.-5 Change of K_{30} in subgrade and base construction

$$K_{PFWD}=\gamma \cdot K_{30} \qquad (4)$$

Gravel: $\gamma=2$, Sand: $\gamma=1.5$, Volcanic cohesive soil: $\gamma=1$

In case of calculate CBR from PFWD measurement result, E value is converted by formula 5. Similarly, it can be converted to unconfined compressive strength by formula 6 (only stabilized soil).

$$E = 10 \times CBR \qquad (5)$$

where E : Elastic modulus on subgrade (MPa)

CBR : CBR in subgrade (%)

$$E = 200 \times qu \qquad (6)$$

where qu : Unconfined compressive strength (MPa)

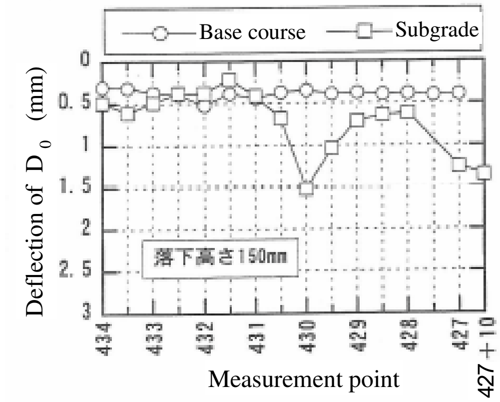
4. Examples

4.1 Subgrade and base course

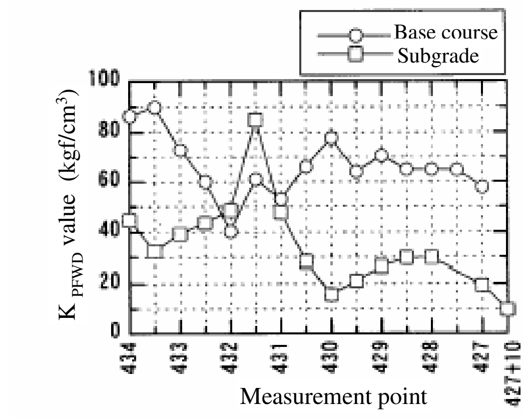
This section introduces several examples of using PFWD for compaction control on embankment, subgrade and base course.

Sekine examined variously compacted embankments using PFWD, to apply K value to compaction control on embankment for railways.

The dispersion of compaction density, air void and K_{30} is reported in the paper by Abe and Kamiura[3), 4)]. They show larger value than coefficient of variation of compaction density. In K_{30}, it is 8 - 18%.



(a) Change of deflection D0



(b) Change of K_{PFWD} value

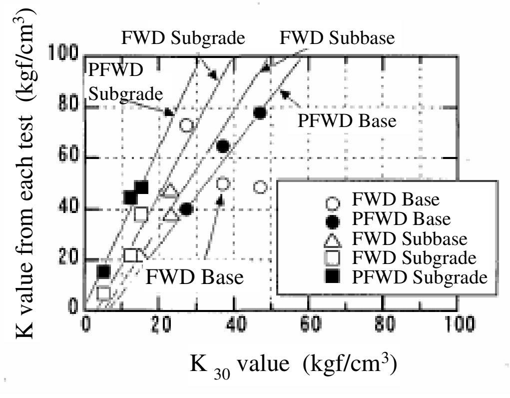
Fig.-6 Change at subgrade and base construction

4.2 Road Pavement

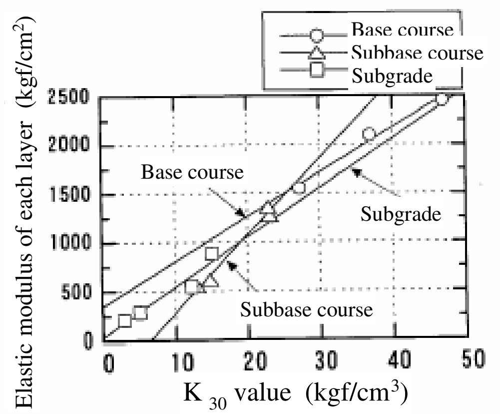
Prof. Sato, etc reports an application example of PFWD on pavement construction[6)]. Fig.-5 shows the relation between K_{30} on subgrade, subbase course and base course. It is confirmed that K_{30} gradually increases in the process of paving layers, however, at the point of No.432, K_{30} on base course was about the half of estimated value from measurement result of subbase course. It is assumed that the density of base course or water content affected.

Fig.-6 shows change of D0 and K_{PFWD} on subgrade and base course. Deflection just below the loading point is uniform on base course. Considering the result from subgrade and subbase course, it is apparent that K value shall be calculated using 2 layer analysis.

Fig.-7 shows calculated E value and K at subgrade, subbase course and base course from the test result by PFWD and FWD. K value from PFWD and FWD is 1 to three times



(a) K value from each test



(b) The K value and the elastic modulus of each layer

Fig.-7 The calculation of the E and the K value with multi- layer by the PFWD

larger than K_{30} from plate loading test. This is due to the difference between static load and impact load, or the effect of mass of subgrade material.

The relation between elastic modulus analyzed by exterior sensor and K_{30} is almost correlative.

From those studies, it is clarified that the rigid evaluation using FWD or PFWD can be applied for quality control test on site.

4.3 Applicability of PFWD at the reinforced concrete deck slab [7)]

A study was conducted on the damaged RC deck slab on the bridge in Tokyo, which includes crack investigation and deflection measurement using PFWD, to examine soundness of RC deck slab.

The structure of bridge deck is shown in Fig.-8. It has not

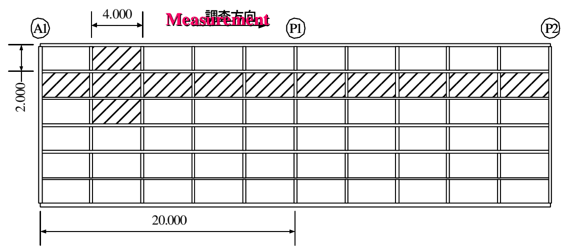
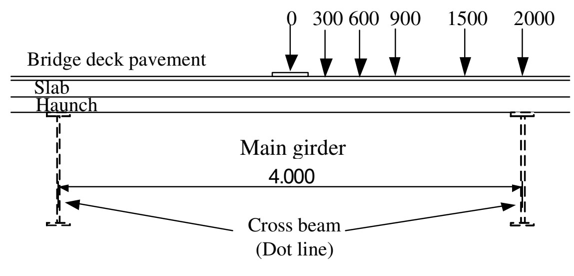
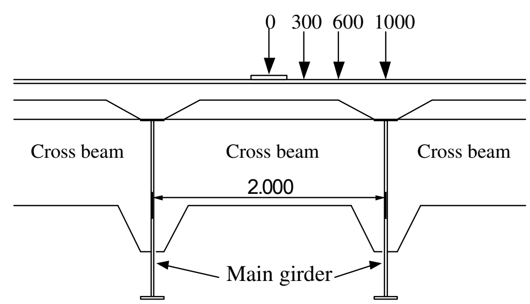


Fig.-8 The structure of the 3 span RC deck slab with 1 span 20.4m



(a) direction of the bridge axis



(b) direction of the bridge axis right angle

Fig.-9 The loading position of the PFWD on the RC deck slab

been rehabilitated since 1976. Crack density between A1 - P1 is 10.43m/m^2 in 1986, and 14.75 m/m^2 in 2003. Measurement section is 4m (bridge axis direction) x 2m (at right angles to bridge axis direction) which is surrounded by main girder and cross beam.

3 sensors including 2 external sensors are furnished in PFWD as shown in Fig-9. The measurement points are 0, 300, 600, 900, 1500, 2000mm in bridge axis direction and 0, 300, 600, 1000mm in right angles to bridge axis direction.

Fig.10 shows relation between deflection and area of deflection basin. The area in sound bridge deck is small due to less measurement point. On the measurement point where crack ratio is large, the deflection of loading point and deflection area changes dramatically.

1 Level which requires rehabilitation over 10 m/m^2 crack

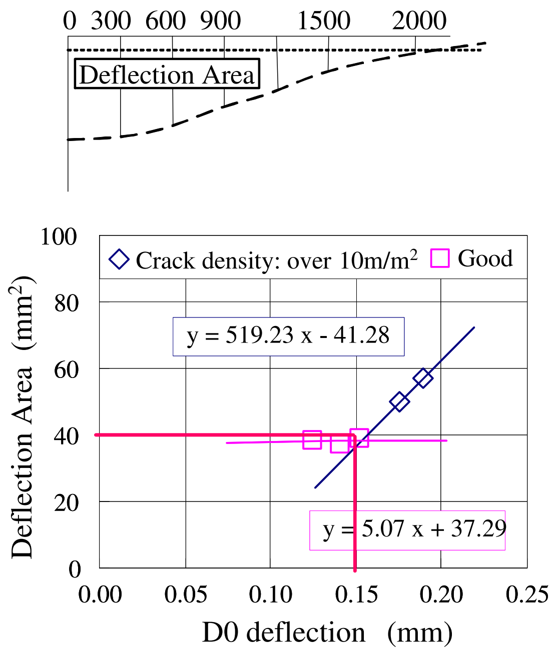


Fig.-10 The relation between the deflection and the deflection area by PFWD

ratio is,

FWD: D0 – 0.18mm, deflection area - 80mm^2

PFWD: D0 – 0.15mm, deflection area - 40mm^2

This might be adopted as judgmental standard for rehabilitation.

- It is easy to operate PFWD in small space; it enables to downsize traffic control. However, it takes longer measurement time at one point than in-vehicle type FWD.

4.4 Construction management for base course and subgrade at airport

This is an example of using PFWD as quality control test for filled embankment, subgrade and subbase course at the airport in Kyushu in 2003.

The gradation of filled embankment at airport varies depends on the mountain where soils are obtained. Each material is uniformly compacted for 1.5m to construct subgrade (Fig-11 & Table-3). Fig.-12 shows the relation between K_{75} from construction management and K value from FWD/PFWD on testing embankment. In the construction management standard for airport, it establishes management value of K_{75} for bearing capacity of subgrade and base course. Therefore, it is judged on site using K_{PFWD} which is obtained from PFWD.

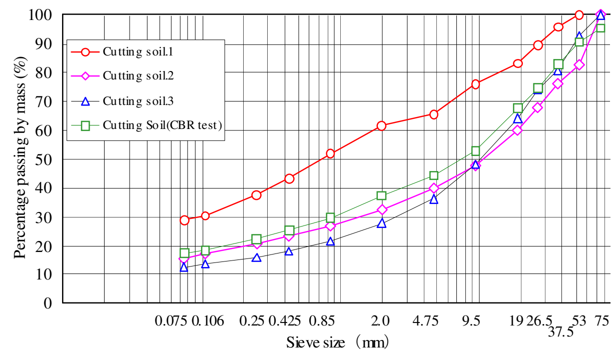


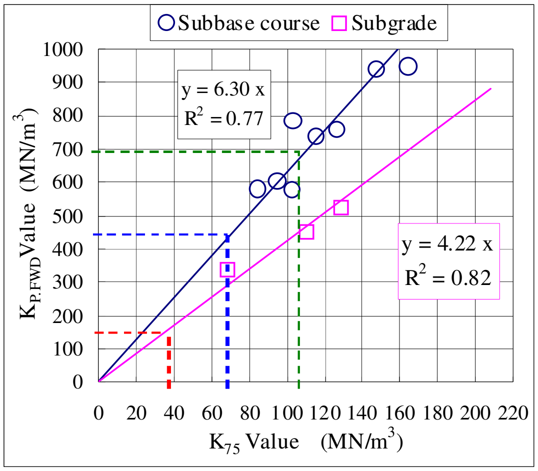
Fig.-11 Sieve analysis of embankment materials

Table-3 The compacting test for the subgrade building

Item		Combined roller & tire roller (Under FL-750), Vibration roller (19t) & tire roller (Over FL-750)			
		FL-1000	FL-750	FL-350	FL-0
Settlement percentage (%)			6.3	20.3	26.6
Degree of compaction (%)		89.1	89.4	94.1	94.3
Wet density (g/cm^3)		2.094	2.000	2.140	2.088
Dry density (g/cm^3)		1.933	1.949	2.042	2.047
K_{PFWD} Value	D=100			363.4	452.4
(MN/m^3)	D=200		226.5		
E_{PFWD} Value	D=100			77.9	97.0
(MN/m^2)	D=200		48.6		
K_{30} (MN/m^3)		—	—	—	281.9
K_{75} (MN/m^3)		—	—	—	118.7
Construction condition		Standard model		Thick layer compaction	

If the density of lower layer is high and reaction is obtained, increase the layer thickness and roll with vibration roller (19t) to increase the density and compaction degree of top layer. Then, it fully satisfies construction management standard (K_{PFWD} 250 MN/m^3, K_{30} 108 MN/m^3 and K_{75} 40 MN/m^3).

- Embankment material (subgrade) contains much fine graded material and less gravel, so compaction degree decreases if it is compacted with large vibration roller. Preliminary rolling using combined roller and tire roller



The quality control target applies the following at K_{PFWD} value.

Subgrade (PFWD)	170	(MN/m^3)
Subbase course (FWD)	450	(MN/m^3)
Base course (FWD)	690	(MN/m^3)

Fig.-12 The quality control value of the subgrade and subbase by the PFWD

with thin thickness achieves good result.

- The rigidity of subgrade might be affected and does not obtain the strength of upper layer. It is important to select compacting equipment size and number of compaction is important.
- This case was implemented to advance the quality control when building and in the revision of the design document in 2000, a quality control technique by the FWD was recommended simultaneously with introduction of the performance based design.

4.5 Interlocking Block Pavement[8)]

The purpose of measuring Interlocking Block Pavement (ILB) with PFWD is to evaluate bearing capacity of base course and subgrade, structure of pavement and load transfer efficiency.

Fig.-13 shows typical structure of ILB with leveling course, cushion sand and joint sand. The measurement of displacement and evaluation using PFWD is described below. It is desirable to use loading plate with diameter 90mm or 100mm.

1) Evaluation of bearing capacity of base course on traffic road

- Measure the displacement with PFWD on the surface of base course, then evaluate by elastic modulus (E).

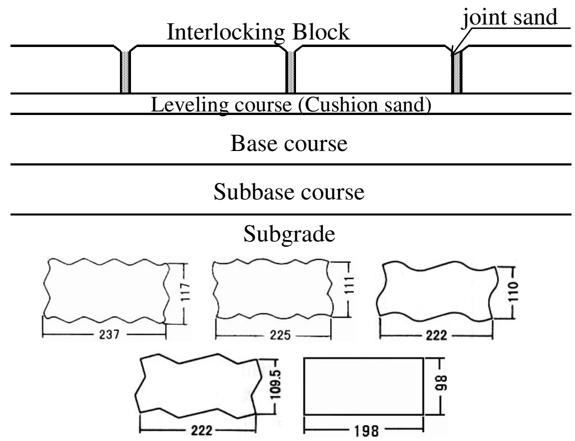


Fig.-13 The structure of the ILB pavement and the shape of general ILB block

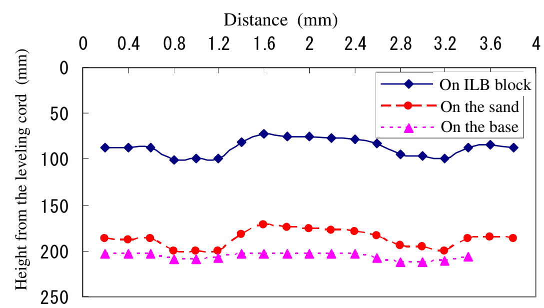


Fig.-14 The deformation shape of each layer of the pavement by the leveling cord

2) Evaluation of bearing capacity of damaged ILB pavement or layer under base course

- When the rutting is occurred or the block is damaged on traffic road/pedestrian road, evaluate the rigidity on ILB or base course immediately and explore the cause of deterioration.
- In addition to measuring displacement on the block, it is also possible to measure on base course when several blocks are removed. The cause of deterioration is clarified by evaluating ILB structure from the displacement.

3) Evaluation of load transfer efficiency on ILB

- The effect of interlocking is evaluated by load transfer efficiency, which represents load transfer from the surface of the block to adjacent block through joint.

This is an example of the evaluation where rutting is

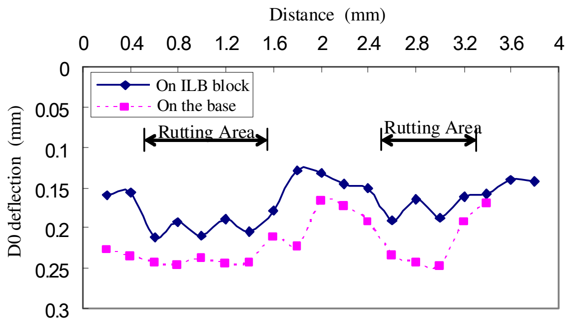


Fig.-15 The deflection D_0 in each pavement layer

occurred on ILB. Fig.-14 shows cross section profile of surface, sand cushion surface and subgrade surface in flow-resistance ILB. Fig.-15 shows deflection D_0 of ILB surface and subgrade surface. From these figures, it can be read that the rutting is caused by deformation of base course, and deformation in the section of rutting is larger than non-rutting section. It can be also presumed that the bearing capacity at the section with rutting is decreased.

5. Conclusion

This paper reports the history of PFWD and its evaluation method for various grounds.

Since the development of easy and convenient equipment for measuring bearing capacity, like Asai type, recent technology has developed new PFWD to measure and evaluate various ground as subgrade and base course, RC deck slab and interlocking block pavement.

Moreover, many handbook and standard for PFWD has been published and PFWD is being popularized as the equipment to ensure high quality and performance.

PFWD was developed as portable testing equipment which costs only 10% of FWD. Its measurement target is the ground which has smaller strength and rigidity due to small loading, but it has ability to measure other measurement subject as park pedestrian road or ground.

【References】

1) Shinichiro Asai: The measurement of the bearing capacity of ground by the impact load, *Japan Society of Civil Engineers magazine*, Vol.42, No.5, pp.17-22, 1957. (in Japanese)

2) A. O. Bohn : Danish Experiments with the French Falling Ball Deflectometer, *The Proceedings of 2nd International Conference on Structural Design of Asphalt Pavements*, pp.647-650, 1967.

3) Nagato Abe, Etuo Sekine, Masaki Kamiura, Teruhiko Maruyama, Yasuo Miura: Stability Processing Evaluation Method for the Subgrade using the HFWD, *5th International Conference on the Bearing Capacity of Roads and Airfields,* pp.301-310, 1998.

4) Masaki Kamiura, Etsuo Sekine, Nagato Abe, Teruhiko Maruyama: Stiffness evaluation of the subgrade and granular aggregates using the portable FWD, *The 5th Unbound Aggregates in Road Construction,* pp.217-226, 2000.

5) Atsushi Kasahara, Makoto Furukawa, Yasuhiko Ito: The development of the handy FWD, JRA, *Japan Road Conference*, No.19, pp.314-315, 1991. (in Japanese)

6) Kenichi Sato, Nobuo Yoshida, Hideaki Tanaka, Atsushi Ideriha, Kenji Nagatani: Evaluation of the bearing capacity of road pavement using the FWD, JSCE, *Journal of Pavement Engineering,* Vol.3, pp.67-72, 1998.12. (in Japanese)

7) Nagato Abe, Mikio Sekiguchi: The reviewing of application to the highway bridge reinforced concrete slab soundness evaluation by the Portable FWD, JSCE, *The 59th art and science annual lecture meeting*, No.1, pp.1237-1238, 2004. 9. (in Japanese)

8) Corporation interlocking block pavement technological Institute Episode: The interlocking block pavement design and construction manual, 2007. 3. (in Japanese)