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Technical note

Embedded shear wave transducer for estimating stress and modulus of As-constructed unbound aggregate base layer

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HIGHLIGHTS

- Embedded shear wave system (ESWS) is applicable to aggregate-size particles.
- ESWS can be placed in the wheel path to measure modulus properties under loading.
- ESWS can be used for estimating in-situ stress & modulus of base layer at any depth.
- ESWS can provide variation in modulus of base layer for moisture content changes.
- ESWS can offer monitoring without road system disturbance and transportation delay.

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ABSTRACT

Resilient modulus is a key property of unbound aggregate layers for construction quality assurance and mechanistic-empirical pavement design. Nondestructive testing methods, such as the falling and light-weight deflectometers, GeoGauge, and seismic techniques, can furnish modulus properties based on the measurement of deflection or seismic waves on the surface of pavement. However, their influence depth or applicability is limited and backcalculation process is required to estimate individual pavement layer moduli. This paper demonstrates the development and field application of a new bender element system as embedded transducer which can estimate the in-situ stress and modulus of aggregate base layers at any desired depth and orientation. An embedded shear wave system (ESWS) using the bender elements was developed for the characterization of a constructed aggregate layer. A power relationship between the shear wave velocity and applied confining pressure was established in laboratory tests to evaluate the average stress state of constructed aggregate layers by using shear wave transducers. The field test results show that the shear modulus of the constructed aggregate layer increases as the moisture in the field evaporates. In addition, the shear modulus estimated under the weight of a super-single tire is greater than that estimated without a load on the surface layer. The ESWS is a promising development for evaluating magnitudes and changes in in-situ stress and modulus according to laboratory calibrated test conditions, and showed a potential for measuring base/subbase modulus at any layer depth during and after construction.

1. Introduction

Aggregate base/subbase layer modulus is one of the most important properties for construction quality assurance and mechanistic based pavement design and evaluation. Resilient modulus (M_R) is used as the main layer property input into mechanistic-empirical (ME) pavement design procedures. Resilient moduli of aggregates can be determined either from laboratory tests or from field testing. Several state agencies follow different test protocols and adapt different field testing methods [1]. Regardless of testing methods, various empirical correlations for the estimation of M_R as a single layer modulus input lack accuracy, because M_R of a constructed granular base mainly depends on applied wheel load stress.

One of the standard laboratory testing methods for M_R is the AASHTO test protocol T-307, which uses the repeated load triaxial

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equipment to apply typical stress states. For more reliable results of the resilient modulus tests, high quality core samples are needed to be retrieved from the field and applied field stress states that are typically unknown need to be matched for M_R estimation. Among different nondestructive field testing methods, falling weight deflectometer (FWD) and light weight deflectometer (LWD) are more commonly used to determine the moduli of the aggregate base and subgrade layers [2–4]. However, FWD backcalculation analysis is necessary to determine the base course modulus with non-standardized software [5–7]. Based on seismic methods such as spectral analysis of surface waves (SASW) and multichannel analysis of surface waves (MASW), portable seismic pavement analyzer (PSPA) was developed to offer modulus profiles estimated at small strain [8–11]. However, the inversion process and assumption of homogeneous and horizontal layers are also required for the PSPA. As another portable device, GeoGauge provides the modulus calculated from the stiffness measured on the surface of aggregate base or subgrade, but the calculated modulus should be considered as the one determined within the shallow-depth influence zone [12,13].

Bender element (BE) has been widely used to measure the shear waves in granular materials in both laboratory and field. Among the field applications of the BE, Yoon et al. [14] developed a field probe including the BE to measure the shear wave in clay soils up to 30 m depth. For the BE application to pavement, Zeng [15] developed a pair of crosshole-type cone penetrometers fitted with the BE for the characterization of shear modulus of soils. However, for the existing devices, the travel distances for shear waves were limited to smaller than or equal to 20 cm, which are shorter than the width of a typical tire applying load on the pavement. Furthermore, the devices were applicable only for the clay- or sand-size particles, which are different from the gradation and compaction characteristics of base/subbase layers. Recently, Byun and Tutumluer [16] demonstrated that the BEs placed at different layers were used to quantify the increase in shear modulus near the geogrid in the geogrid-stabilized aggregate specimens in repeated load triaxial test, showing the possibility of using the BE in the dense-graded unbound aggregate layers in field. Although the strain level for shear modulus estimated from using the BE is smaller than that for resilient modulus, the BE can be effectively used for monitoring the modulus change of aggregate layers, because the shear waves are measured in elastic deformation range without any disturbance of sample. Further, the shear waves obtained from a certain direction oriented to the BE layer can represent the modulus properties of localized zone. Nevertheless, the shear modulus monitoring concept based on the embedded BEs has not yet been applied in a field constructed aggregate layer but only to aggregate specimens in laboratory tests.

This paper presents the development and application of an embedded shear wave system (ESWS) for constructed aggregate layers using BE type embedded shear wave transducers. First, the ESWS including the BEs is introduced with proper consideration of the BE dimension, wave travel distance, BE protection, and mounting frame. The scope covers the laboratory characterization of aggregate materials and the field application in a constructed aggregate layer test section where the ESWS was embedded. The differences in the measured shear waves are reported in accordance to applied wheel loading (stress induced) and the dry and wet soil moisture conditions. Finally, the estimation of in-situ stress and modulus with the laboratory calibrated ESWS is discussed for its promising practical use in pavement design and evaluation.

2. Embedded shear wave system

In this study, Bender elements (BEs) were used to estimate the modulus properties of a constructed aggregate base layer. As a shear wave transducer, the BEs, which consists of a central metal shim and two sheets of piezoelectric materials, can generate and detect the shear waves based on the phenomenon of piezoelectricity. Compared to ultrasonic transducer, the BE has better coupling with granular materials, and the cost of BE is relatively lower. Thus, it is possible to embed the BE within the aggregate layer for monitoring the modulus change in the field at any depth and orientation. Fig. 1(a) shows the sheets of BEs with 20 mm width and 30 mm length. Based on wave mechanics, the wavelength of shear wave generated from the BE increases as the length of BE increases. To minimize the internal low-pass filtering effect in granular materials, it is also known that the wavelength should be longer than twice median particle size [17]. Considering typical mean diameter of the top size 25 mm dense-graded base course aggregates, the 30 mm length of BE was selected to overcome the internal low-pass filtering effect. Fig. 1(b) shows the BE connected with a coaxial cable. To remove crosstalk on the output signal, the BE was designed as parallel type, and thus the inner core was soldered to the central metal shim of BE, and two lines of twisted outer shield were soldered to both sides of the piezoelectric materials. After insulation between the inner core and outer shield, the surface of BE was coated with a conductive silver paint for better electromagnetic shield.

A base made of brass for mounting the BE is shown in Fig. 1(c) and (d). The base includes two protection bars above and below the BE, which are intended to preserve the BE during compaction process in field. In fact, the same type of a protection bar was effectively used in the previous study reported by Byun and Tutumluer [16]. After inserting the BE in the base, the gap was filled with a high strength epoxy, and the exposed part of the BE had 20-mm length. The boundary condition of the BE fixed by embedding in the base course is similar to that of cantilever beam

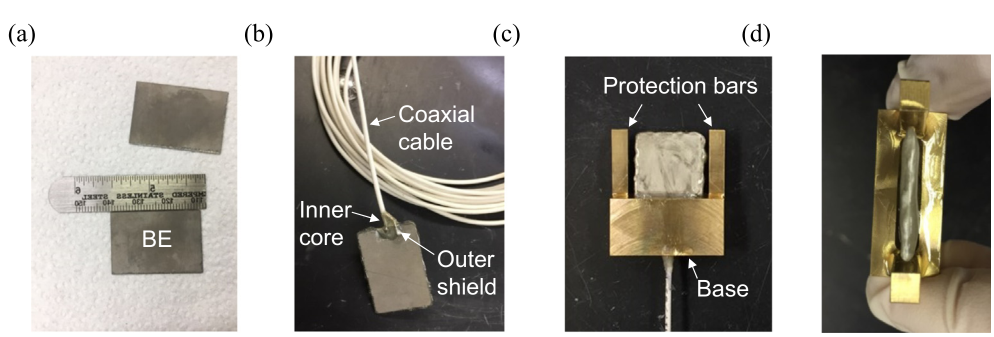

Fig. 1. Bender element (BE) used in this study: (a) BE sheets, (b) BE connected to coaxial cable, (c) BE mounted in base (side view), (d) BE mounted in base (plan view).