Construction and Building Materials 83 (2015) 299–307

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Characterization of hydraulically bound base materials through digital image correlation

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HIGHLIGHTS

- Beneficial effects of slag/cement on compressive strength and elastic modulus.
- Inconvenient guidelines for characterization of cement stabilized material-CSM.
- 3D digital image correlation method is appropriate for CSM characterization.
- Strong correlation between compressive strength and CSM modulus of elasticity.
- Possible prediction of elastic properties of CSM using presented equations.

ARTICLE INFO

Article history:
Received 15 December 2014
Received in revised form 20 February 2015
Accepted 4 March 2015

Keywords:
Digital image correlation
Ultrasound pulse velocity
Pavement
Base course
Modulus of elasticity
Steel slag

ABSTRACT

Accurate design of pavement behavior requires elastic properties of all the constituting layers. Measuring of elastic modulus on crude surfaces, by contact based mechanical devices, often results in a high dispersion of determined values. Therefore, application of multiple measurement methods on six different mixtures is presented, among which an innovative approach using spatial digital image correlation. Obtained results indicate that there is a strong correlation between the compressive strength and the dynamic and static modulus. Thus, by using presented equations it is possible to predict elastic properties of cement bound aggregate by measuring just one of the relevant parameters.

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1. Introduction

Pavement base course hydraulically bound materials can be defined as a mixture of aggregate, small amount of binding agent (Portland cement) and water, which hardens after compaction and curing to form a durable paving material. These materials are by composition similar to concrete and in literature are also known as low strength concretes or lean concretes. They are equally utilized in pavement structures (containing stabilized base course) made of asphalt or concrete, and represent an important design element. Since asphalt is more flexible, the hydraulically bound base course provides additional strength and support, without the necessity of increasing the total thickness of pavement layers. By maintaining a lower thickness, i.e. by avoiding thickness increase, an engineer enables faster construction work and thus better use of valuable resources [1]. Furthermore, a stiffer base reduces deflections due to heavy traffic loads, thereby extending pavement life and reducing maintenance costs. When used in concrete pavements, this layer prevents the emergence of material "pumping".

In order to predict pavement behavior under load adequately, material characteristics of all the pavement-constituting layers must be known. Characteristics necessary for behavior prediction are elastic modulus E and Poisson's ratio ν, for determination of which there are various laboratory and in situ methods. Additionally, various analytical expressions provide static or dynamic elastic modulus values based on known material compressive strength. Determination of compressive strength is relatively straightforward. But measuring of elastic modulus on materials with crude surfaces, such as base course, with conventional, contact based, mechanical devices is often time consuming with great dispersion of results.

In light of mentioned issues this study evaluates elastic properties (dynamic and static modulus of elasticity) of CSM (cement-stabilized material) made of natural gravel, steel slag as

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http://dx.doi.org/10.1016/j.conbuildmat.2015.03.033
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an alternative aggregate and various amounts of cement binder (2% and 4%). The aim and scope of this study is to provide additional data on modulus of elasticity of cement-stabilized materials used in road construction. The objective of this study is verification of adequacy of different test procedures for measurement of CSM elastic properties. Additional value is gained through comparison of results obtained by various applied methods, which are also used to assess the possibility of CSM elastic properties prediction based on measured compressive strength.

2. Methods for characterization of cement stabilized material

Cement stabilized mixtures (CSM) for usage in road construction are usually characterized by the 28th day compressive strength. However, in recent years pavement design has reoriented from an empirical to a more mechanics based approach, on the principles of elastic theory [2,3]. For an effective design based on the elastic theory, elastic properties of pavement materials are required [4].

2.1. Static modulus of elasticity according to EN 13286-43

For hydraulically bound mixtures, standard test method for determination of the modulus of elasticity is defined in EN 13286-43 [5]. Guidelines in this norm suggest that modulus can be determined based on the compressive strength test, the direct tensile test or the indirect tensile test. Even though these static testing methods are usually used for CSM characterization, there are several problems in doing so. First of all, the results quality depends on the rate of loading, deformation effects and stress level at which elastic properties are determined [6]. Cement stabilized materials are porous so the applied forces during the compressive strength test crush the material and change its porosity even at lower rates of stress then the prescribed 30% of σ_u. In addition, porosity change depends on the magnitude of applied loading. Thus, the measurement and accuracy of determined elastic properties are questionable. Secondly, direct evaluation of the static modulus of elasticity is a complicated and time-consuming procedure [7]. It is why researchers and practitioners rely on the much easily determined dynamic modulus of elasticity, which is most often defined by the non-destructive method of ultrasonic pulse velocity.

2.2. Ultrasonic pulse velocity method

Ultrasound pulse velocity (UPV) measurement is one of the standard tests for materials properties determination and its use is defined in EN 12504-4 [8]. In addition to evaluating the dynamic modulus of elasticity, ultrasound pulse velocity can be correlated with the compressive strength. This relatively simple test is commonly applied in assessing the performance of hardened concrete [7,9–12] and can be successfully used in CSM characterization [13].

UPV measurement is not affected by the curing condition [9] which makes it particularly suitable for in situ characterization of road construction materials. Pavement imbedded materials curing condition is emphasized by the fact that curing depends on weather conditions.

When using UPV measurement for cement stabilized materials, impulses in a frequency range of 20–250 kHz are to be used [13], while ultrasonic pulses in the range of 40–80 kHz are suitable for the evaluation of concrete properties [10]. Beside the frequency range, the transducer size can affect the measurement results, primarily through velocity readings. Larger transducers (5 cm diameter) can detect higher velocities than those determined by small transducers (0.7 cm diameter) [11]. In light of given findings ultrasonic pulse testing done through the course of this study was conducted using a 5 cm diameter transducer with a frequency of 45 kHz.

The calculation of pulse velocity is done according to the relevant norm [8] and the calculation of the dynamic modulus is done using Eq. (1):

$$E = \rho \cdot v^2 \cdot \frac{(1+\nu)\cdot(1-2\cdot\nu)}{1-\nu} \quad (1)$$

where v is pulse velocity (m/s), ν is the Poisson's ratio and ρ is the material density (kg/m^3).

To limit the error introduced by imperfect transducer–specimen contact, the specimen can be emerged in water, but the presence of water requires two experimental set-ups and measurements to isolate the velocity of sound through the specimen without the influence of water [14]. In order to bypass this problem UVP measurement in this study was done using ultrasonic gel couplant, which ensures a suitable contact between the transducer and the specimen.

2.3. Spatial digital image correlation (3D DIC)

Digital image correlation (DIC) is a non-destructive and non-contact method used for determination of a loaded object surface deformation, firstly proposed at the beginning of the 1980s [15]. The fundamental operating procedure is comparison of images taken under different loading conditions, achieved by dividing taken images into small subareas and tracking these subareas movement in comparison to the "zero" position (before load is applied). The use of this technique therefore enables measuring of an area full field deformation, which makes it useful for determining the collapse mechanism on various material specimens. With an insight into the whole deformation field it is possible to completely reconstruct the crack geometry without extensive instrumentation [16].

Due to the coarse surface of specimens used in this research, a 3D DIC measurement is advantageous in comparison to classic, mechanical devices that are contact based. Namely, the contact between an extensometer and the specimen is compromised during loading due to the roughness of surface and slight movements. One should attach an extensometer at points that are not in surface indentations and maintain the specified measuring base, but also avoid inclinations to the specimen wall. Such conditions are very difficult to obtain, especially when the elastic strain is relevant. In addition, point-to-point measurement can often be misleading, especially when dependence related to the heterogeneous nature of strain and strain localization phenomena [17] are taken into account. Aside the disadvantages of the classic approach, 3D DIC technique can record deformations at similar strain resolution levels and the tested surfaces of the specimen do not have to be planar, nor the cameras need to be positioned perpendicular to the observed surface(s) [18]. Moreover, out-of-plane deformation of a surface can be neglected during calculations, which assures a higher accuracy level.

Testing with a DIC system requires more preparation than with classical instruments, but once properly set up the processing time per specimen is comparable, if not better. Testing preparation includes measuring volume determination, system calibration dependent on the selected measuring volume and if necessary specimen treatment. The calibration of cameras is done using certified coded calibration panels size of which are dependent on the measuring volume. Prior to calibration, angle relations of the lenses, focus and aperture have to be set. Specimen treatment is done when its surface does not have enough characteristics for pattern recognition, most often by applying a color spray stochastic pattern. The testing itself is no different than with mechanical extensometers since the process of recording images can be automated. Image recording is done simultaneously with the acquisition of the analog inputs from the test machine (e.g. force and displacement signal). System software recognizes surface patterns on digital images of the measuring object and allocates coordinates to image pixels.

Spatial DIC measurement for the purpose of this study was implemented using Aramis 3D optical deformation analysis system, developed by GOM (Gesellschaft für optische Messtechnik). Fig. 1 shows Aramis main hardware components together with the rest of the test setup. Basic Aramis hardware units are two cameras (sensor), stand for secure and steady hold of the cameras, specimen L.E.D. lighting, sensor controller and power supply of the cameras, and a high-performance PC system [19]. The PC system is equipped with an appropriate software package [20]. The digital cameras support a resolution of 2448 × 2050 pixels and are equipped with a CCD chip. The lens have a focal length of 12 mm and they are set at an angle relation of 25°. In order to ensure a full view of the specimen volume during all loading stages the cameras were mounted at a distance of 470 mm from the cylinder face and were set to form a distance of 170 mm between each other. For this camera alignment, 0.015 mm^2 on the specimen surface represents a pixel on the image. With given hardware components a strain accuracy of up to 0.01% is established [19], which is at all times controlled by the units software monitoring of the mean points intersection deviation that is kept at lower than 0.1 pixel.

Since the specimen surface lacks contrast in its natural state, it was evaluated that a white color spray would enable adequate pattern recognition in an area of 19 × 19 pixels. A prepared test specimen used in this research is shown on Fig. 2c, together with its nominal dimensions and natural state.

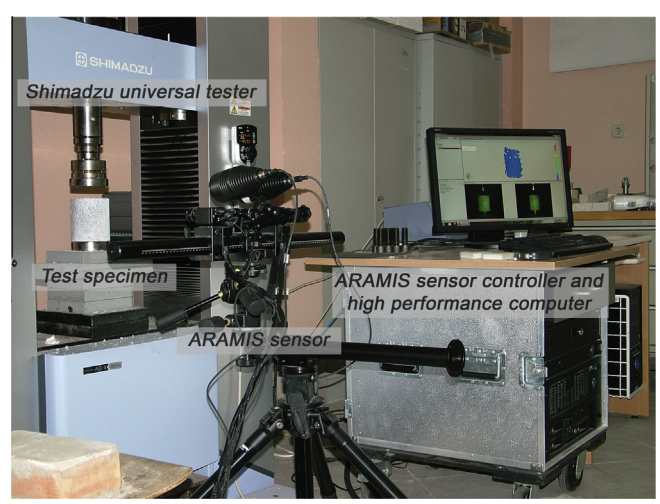

Fig. 1. Test setup for 3D DIC measurement.

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