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Research Article

A Methodology for Determination of Resilient Modulus of Asphaltic Concrete

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Resilient modulus, M_R, is an important parameter for designing pavements. However, its determination by resorting to cyclic triaxial tests is tedious and time consuming. Moreover, empirical relationships, correlating M_R to various other material properties (namely, California Bearing Ratio, CBR; Limerock Bearing Ratio, LBR; R-value and the Soil Support Value, SSV), give vast variation in the estimated results. With this in view, an electronic circuitry, which employs bender and extender elements (i.e., piezo-ceramic elements), was developed. Details of the circuitry and the testing methodology adopted for this purpose are presented in this paper. This methodology helps in determining the resilient modulus of the material quite precisely. Further, it is believed that this methodology would be quite useful to engineers and technologists for conducting quality check of the pavements, quite rapidly and easily.

1. Introduction

Resilient modulus, M_R, generally corresponds to the degree to which a material recovers from external shock or disturbance. This property of the material is actually an estimate of its modulus of elasticity, E. In case of slowly applied load, slope of the stress-strain curve in linearly elastic region yields E, whereas, for rapidly applied loads (e.g., load experienced by pavements), this would yield M_R. The resilient modulus can be expressed as

$$M_R = \frac{\sigma}{\varepsilon_r}, \tag{1}$$

where σ is the applied stress and ε_r is the recoverable axial strain.

M_R describes the mechanical response of a pavement base or subgrade to the applied cyclic (traffic) load, and, hence it is considered to be an essential parameter for pavement design. By knowing the resilient modulus for the subgrade soil and the pavement material, the structural behavior of the pavement against traffic loading can be ascertained.

However, obtaining M_R is a very difficult task, and it can only be determined by laboratory testing of the material [1–3]. As such, the Long Term Pavement Test Protocol (LTTP) P46 is widely used [1, 4, 5] for determining M_R, which in turn requires dynamic triaxial testing on cylindrical cores. Several other (modified) methodologies such as National Highway Research Program (NCHRP) 1-28A method and Federal Highway Administration (FHWA) method (1) are also employed for determining M_R. Various empirical relationships, correlating M_R to other material properties (namely, California Bearing Ratio, CBR; Limerock Bearing Ratio, LBR; R-value and the Soil Support Value, SSV) can also be employed to estimate M_R. However, these relationships give vast variation between the estimated and experimental results [4–6]. In addition to the material properties, M_R value depends upon many of the testing parameters like preparation technique, loading amplitude, sequence of loading cycle and the confining pressure. However, not much attention has been paid by the earlier researchers to corroborate laboratory results vis-à-vis field conditions. This necessitates development of a methodology that would yield M_R in a convenient way without compromising the field conditions. Under these circumstances, application of a nondestructive methodology, which is based on propagation of mechanical waves, seems to be a better choice [1, 7]. In recent years, it has been found that some of the nondestructive testing methods (namely, the laser technique, ground-penetrating radar, falling weight deflectometers, mini- or portable lightweight cone penetrometers, GeoGauge, and infrared and seismic technologies) can be successfully employed for the prediction of M_R and for the purpose of quality control and acceptance of flexible pavement construction [8]. However, some researchers [6, 9–11] have found that M_R, determined from the laboratory testing, differs from the nondestructive testing based analysis.

With this in view, attempts were made to determine the resilient modulus of asphaltic concrete cores by employing piezoceramic elements and an electronic circuitry developed by the researchers at the Indian Institute of Technology Bombay, India [12, 13]. In addition, complete characterization of these cores was done as a part of the proposed method for determining M_R. The result obtained from this method was then compared with that obtained from the triaxial loading testing, and it was concluded that piezoceramic elements can be successfully employed for determining resilient modulus in pavement designing.

2. Experimental Investigations

2.1. Characterization of Asphaltic Concrete Cores. DAC (Dense Asphaltic Concrete) and SDAC (Semi-Dense Asphaltic Concrete) cylindrical core samples for this study were obtained from the airfield pavements of the two runways of an airport in India. These cores were extracted from the wearing and binder courses of the pavements of these runways. Density-void analysis, Marshall Stability, and Flow value tests were carried out on these cores as per ASTM D6927 [14], and the results are depicted in Table 1.

The Marshall Stability value of the DAC and SDAC specimens, when tested at 60°C, were found to be 765 kg and 725 kg, respectively. The flow value of the SDAC specimens was found to be on the higher side as compared to that for DAC samples. The average bulk density of the DAC and SDAC specimens was found to be 2.36 and 2.33 g/cc, respectively. The stiffness modulus of the mix was determined based on the parameters of the mix (namely, density, air voids, aggregate voids filled with bitumen, and bitumen content), the properties of the bitumen (namely, penetration, softening point, temperature susceptibility, penetration index, and specific gravity), and the properties of aggregates (namely, specific gravity) by using the Shell nomograms [15], as listed in Table 1. The gradation curves for the samples are depicted in Figure 1.

Table 1: Average properties of DAC and SDAC mix of extracted cores.

Property	Specimen	
	DAC	SDAC
Average diameter (mm)	90	90
Average height (mm)	180	180
Bulk density (g/cc)	2.36	2.33
Air voids (%)	4	6
Aggregate voids filled with bitumen (%)	75	66
Bitumen content (%)	5.5	5.4
Poisson's ratio	0.4	0.4
Penetration value (°C)	58	67
Softening point (°C)	55	47
Temperature susceptibility (A)	0.038	0.049
Penetration index (PI)	0.347	−1.299
Temperature difference (°C)	25	17
Bitumen stiffness (N/m^2)	5000000	4000000
Specific gravity of aggregates	2.75	2.75
Specific gravity of Bitumen	1.007	1.007
Binder volume (cc)	12.9	12.5
Aggregate volume (cc)	81.1	80.2
Stiffness modulus of the mix (MN/m^2)	931.5	750.4
Marshall stability (kg)	765	725
Flow value	2.2	8.35

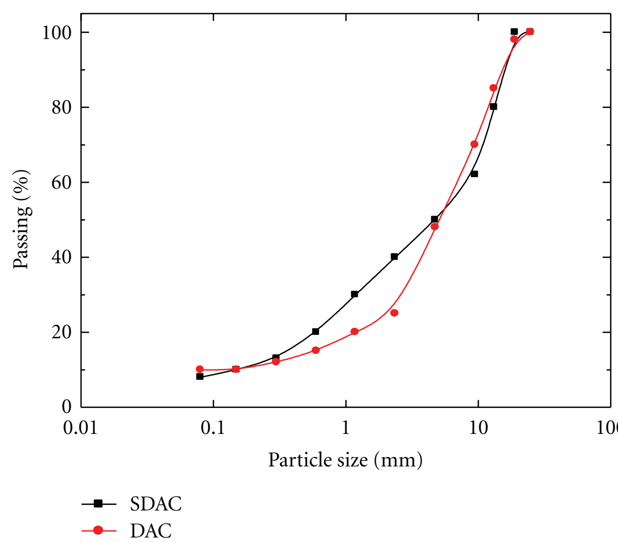

Figure 1: Gradation curves SDAC and DAC samples aggregates.

2.2. Measurement of Shear and Compression Wave Velocities. To determine the shear and compression wave velocities (V_s and V_p, resp.), a simple and cost-effective bender element setup developed by the authors [12, 13] was employed. Signal interpretation and analysis of the results has been done in accordance with the information available in the literature [16–18]. The block diagram of the test setup for measuring V_s and V_p in the cylindrical asphaltic concrete cores has been depicted in Figure 2. As depicted in the figure, on both ends of the specimen, piezoceramic elements (the pair of a transmitter and a receiver) can be fitted. The transmitter is excited with a single-cycle sine wave of certain amplitude, which is generated from a function generator. The receiver

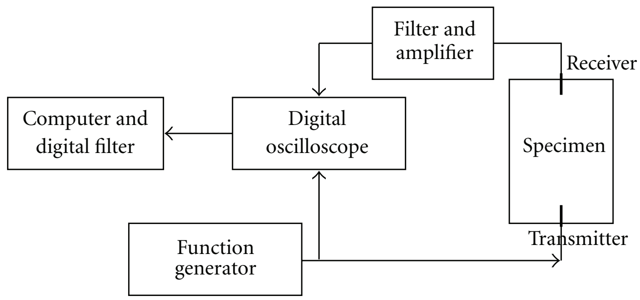

Figure 2: Block diagram of the test setup used for measuring V_s and V_ρ.

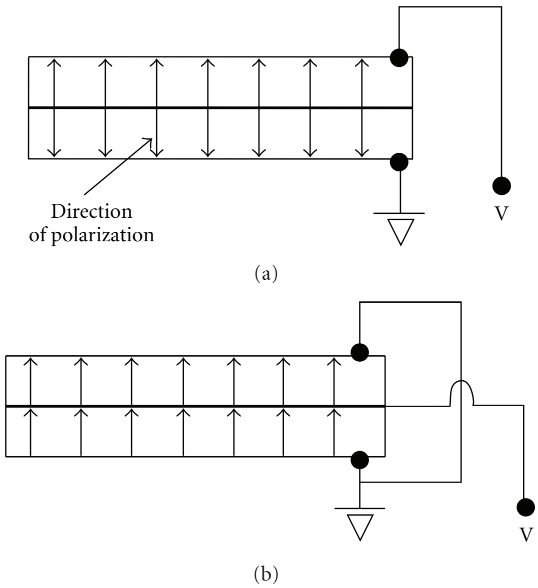

Figure 3: (a) Series and (b) parallel type configuration for bender elements.

is connected to a filter/amplifier circuitry, which in turn is connected to a digital oscilloscope that also receives a direct sine wave or a step signal from the function generator.

Bender elements used in this study were procured from the Centre for Offshore Foundation Systems, The University of Western Australia. These elements were constructed by bonding two piezoceramic materials together in such a way that a voltage applied to their faces causes one face to expand while the other face to contracts. This causes the entire element to bend and generation of a voltage and vice versa. As depicted in Figure 3, the receiver and transmitter bender elements consist of series and parallel bimorph configurations, respectively. The bender elements in Figures 3(a) and 3(b) were subsequently used as extender element, thus producing V_ρ, by inter changing the wiring configurations and direction of polarization, as shown in Figures 4(a) and 4(b).

For determining the time delay introduced in the measurements due to the electronics, ceramics, and coating materials of the bender element, calibration of the complete system was conducted. This was achieved by placing the tips

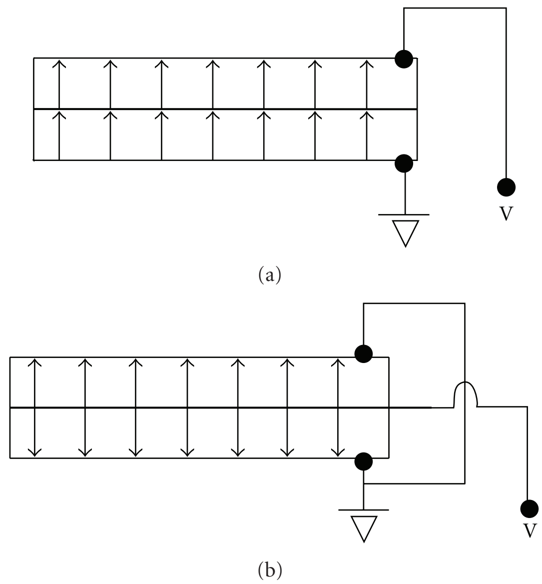

Figure 4: (a) Series and (b) parallel type configuration for extender elements.

of the two bender elements in direct contact with each other and measuring the calibration time t_c between the electrical pulse sent to the transmitter and received by the receiver. It was found that the magnitude of t_c is very small (=5 μs). In addition to this, V_s for an aluminum rod (160 mm × 25 mm × 25 mm), a thermocol (82 mm diameter and 62 mm length) and a M-30 grade concrete (50 mm diameter and 67 mm length), was also measured [11]. To achieve this, thin slits (about 1.6 mm wide and 11 mm long) were created at the centre of each of the two planes, which are perpendicular to the length of the aluminum bar or concrete block. Later, in these slits, which are parallel to each other, bender elements were fitted. For these materials, $V_s$was found to be 3217 m/s, 280 m/s and 1500 m/s, respectively, which match very well with the values reported in the literature [19]. Moreover, V_s and V_ρ were measured on some standard materials. Using (2), [20, 21], Poisson's ratio, ν, when computed for rubber, stainless steel, and cork was found to be 0.5, 0.29, and 0, respectively, matching well with the results in literature [22–24]

$$\nu = \frac{(0.5 \cdot r^2 - 1)}{(r^2 - 1)}, \tag{2}$$

where r is ratio between V_ρ and V_s.

Later, V_s and V_ρ in the DAC and SDAC specimens were measured. A typical waveform obtained for the DAC specimen is depicted in Figure 5.

2.3. Loading Test. A Humboldt, USA, made master loader system (HM 3000) was used for determining M_R. This setup facilitates microprocessor-based stepper motor speed control and consists of analogue-to-digital converter with real-time data acquisition; the motor speed can be selected between 0 to 75 mm/min, with RS-232 interface.

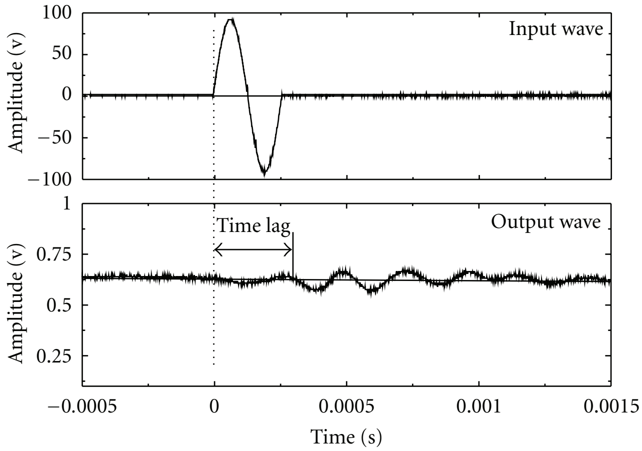

Figure 5: Typical waveform obtained from the test setup for a DAC specimen.

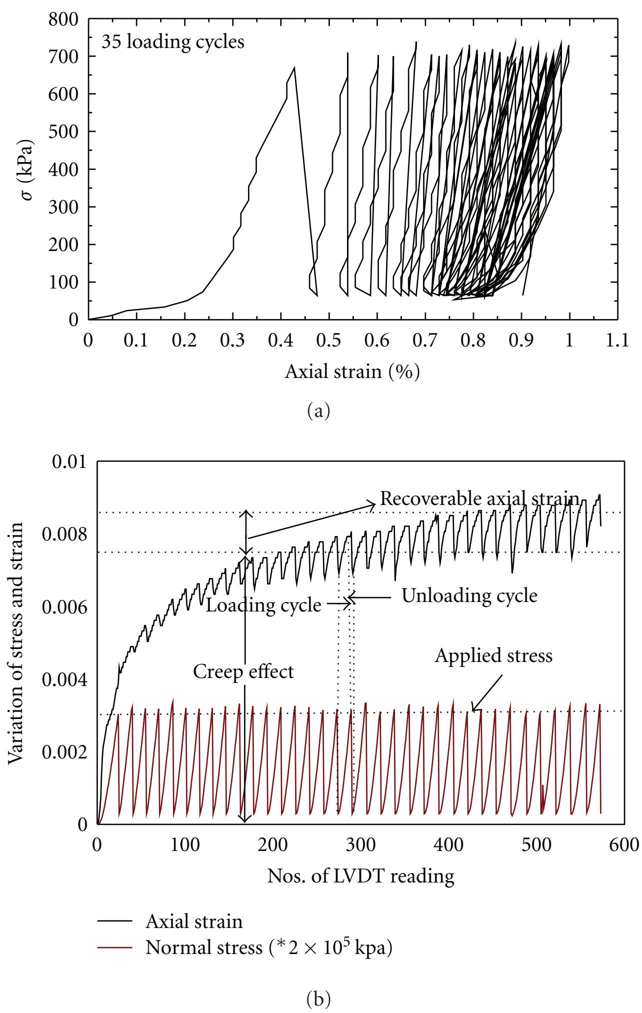

Figure 6: (a) A typical stress-strain curve obtained for a DAC specimen. (b) Stress-strain variation during loading.

Table 2: Shear, elastic, and resilient modulli of different specimens.

Specimen	$G_{\max}$ [MPa]	$E_{\max}$ [MPa]	M_R [MPa]
DAC1	775	2170	1693
DAC2	493	1381	971
SDAC1	249	698	748
SDAC2	387	1085	796

Load was applied on the specimens with the help of computer-controlled user defined test setup program. Before loading the specimens, strain rate was set to 25 mm/min and stop condition was set to: "load exceeding 18 kN," which is based upon the possible elastic modulus values for these samples. Deformation undergone by the specimens was recorded every 1 s by employing a Linearly Variable Differential Transducer (LVDT), connected to the computer controlled user defined setup. Each load cycle followed a time lag of 10 s during which unloading was done. A total nos. of 35 loading cycle was applied to each specimen.

3. Results and Discussions

Low strain shear modulus, $G_{\max}$, and elastic modulus, $E_{\max}$, in the specimens were computed as follows [20, 21]:

$$G_{\max} = \rho \cdot V_s^2, \tag{3}$$

$$E_{\max} = 2\, G_{\max} \cdot (1 + \nu), \tag{4}$$

Where ρ is the mass density of the specimen. ν for the samples was obtained from (2) by using V_s and V_ρ.

A typical stress-strain curve obtained for a DAC specimen is depicted in Figure 6(a). Figure 6(b) exhibits the variation of stress and strain during the loading process. It can be observed from these figures that the variations in these parameters are quite similar to the variation of load and deformation, with time [25]. It must be noted that this concept is widely used for determining resilient modulus by dynamic triaxial testing and applying a haversine pulse loading. Hence, it is believed that the resilient modulus determined by this method would represent the same situation when axle load passes over the pavement.

Recoverable axial strain for the specimens was determined as depicted in Figure 6(b) and using this value, the resilient modulus was determined by using (1). The value of shear, elastic, and resilient modulli are listed in Table 2.

The relationships between M_R with $G_{\max}$ and $E_{\max}$ has been depicted in Figure 7. As suggested by earlier researchers [20, 26], V_ρ/V_s and, hence, ν, for a particular type of material (namely, asphaltic concrete, cement concrete or a particular type of rock) remain the same. Hence, M_R can be correlated to both $G_{\max}$ and $E_{\max}$, as these two parameters are interrelated by ν, which is a function of V_s and V_ρ (ref. (2)). The relationships obtained between these parameters can be expressed as

$$\begin{aligned} M_R &= 2.1 \cdot G_{\max}, \\ M_R &= 0.77 \cdot E_{\max}. \end{aligned} \tag{5}$$

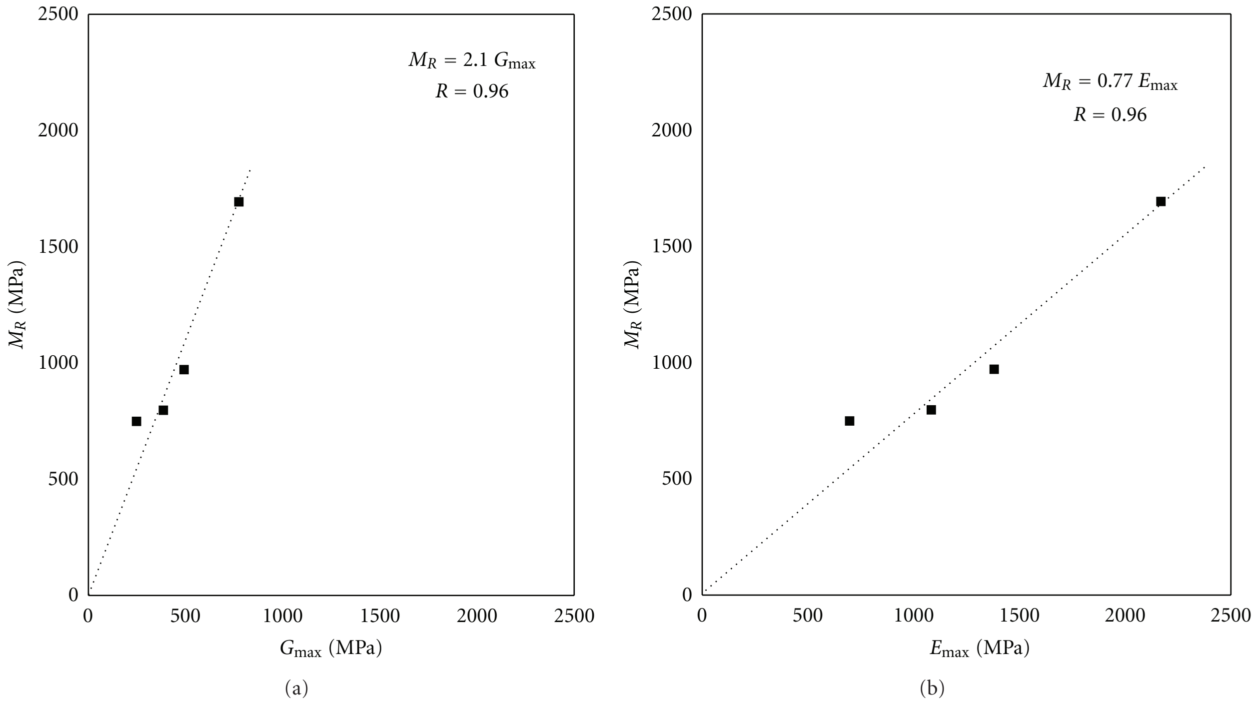

Figure 7: A comparison between M_R with G_{max} and E_{max}.

This indicates that M_R in an asphaltic concrete pavement can be predicted easily with the help of piezoceramic element by measuring V_s and V_ρ.

4. Conclusions

This paper presents details of a novel methodology, which employs piezoceramic elements for determining resilient modulus of the dense and semi-dense asphaltic concrete blocks. It has been demonstrated that this methodology yields results in a very short duration and also without employing costly paraphernalia. The results obtained are found to be quite close to those obtained from conventional cyclic tests. However, extension of this methodology to in-situ conditions requires further investigations.

Nomenclature

E: elastic modulus
G: shear modulus
G_{max}: low-strain shear modulus
M_R: resilient modulus
t_c: calibration time
V_s: shear wave velocity
V_ρ : compression wave velocity
ε_r: recoverable axial strain
ρ: mass density
σ: applied stress
ν: Poisson's ratio.

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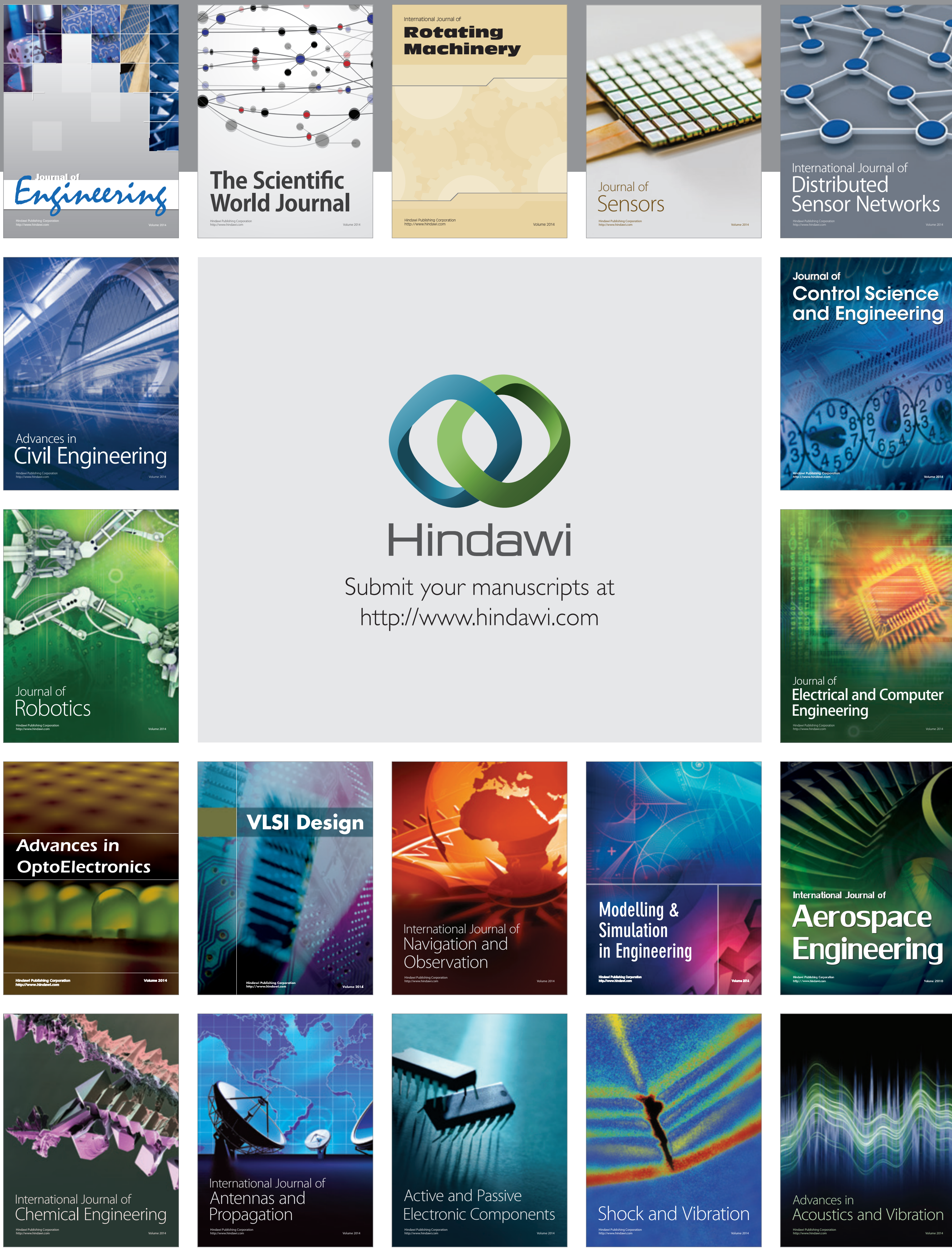
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