



New insights into the use of particle-size sensors for asphalt mixture gyratory and roller compaction

Omar Guazzaroni, Lorenzo Paolo Ingrassia^{*}, Amedeo Virgili, Andrea Graziani, Francesco Canestrari

Università Politecnica delle Marche, Via Brecce Bianche, Ancona, 60131, Italy

ARTICLE INFO

Keywords:

Particle-size sensor
Asphalt mixture
Workability
Compaction
Gyratory compactor
Roller compactor

ABSTRACT

Compaction is a critical phase in pavement construction, directly influencing early performance and long-term durability. While field procedures aim to achieve target density levels, laboratory methods still struggle to fully replicate field compaction mechanisms. Although particle-size sensors have recently been standardized for gyratory compaction through ASTM D8541, the reliability of the associated workability parameters remains uncertain due to machine-specific mold kinematics. The first objective of this study is therefore to assess the consistency and interpretability of ASTM D8541 workability parameters. A second objective is to explore the feasibility of applying particle-size sensors in roller compaction, where no established framework currently exists. To address these aims, two gyratory compactors, one roller compactor, three asphalt mixtures, an unbound granular material, and two sensor geometries were investigated to characterize particle motion under laboratory compaction. Results show that ASTM D8541 parameters are affected by rigid mold movement, leading to inconsistent outcomes across gyratory machines and indicating the need for compactor-specific calibration. A new parameter, M-S RRC, is introduced to quantify the relative motion between mold and sensor, providing an improved and locally measured indicator of compaction effort; in gyratory compaction, it exhibits a favourable indicative trend with the Compaction Energy Index (CEI). Finally, roller compaction tests demonstrate that spherical sensors are more sensitive than cubic ones to variations in mixture workability, supporting their preferential use for detecting subtle differences in compaction behavior.

1. Introduction

The compaction process of asphalt mixtures is a critical phase in road pavement construction, requiring careful attention to ensure adequate performance, as the resulting compaction state strongly influences subsequent pavement deformation and rutting behaviour. Over the years, field compaction equipment has been developed to apply dynamic and static loads for the achievement of the target density level. At the same time, various laboratory methods have been introduced to replicate, or at least correlate with, the mechanisms occurring during field compaction [1]. Laboratory equipment employed to study the asphalt compaction process includes the Marshall impact compactor, the gyratory compactor, and the roller compactor (pneumatic tyre, steel roller or sliding plates) [2]. Several studies have shown that gyratory compaction is the method that best reproduces the internal structure typically observed in pavement cores [3,4]. Other studies have found that rolling

pneumatic tyre compaction can replicate the kneading action of field pneumatic-tyre rollers, while Marshall compaction appears to simulate the vibrating effects observed with field vibratory rollers [5]. Moreover, roller compaction is recognized as the laboratory method that best reproduces the field compaction mechanism [6]. However, none of these methods fully reproduce field compaction, as confirmed by the differences often observed between field cores and laboratory-compacted specimens [7]. Understanding the relationship between laboratory and field compaction is therefore critical for improving consistency between the two, ultimately enhancing both pavement quality control and the reliability of laboratory tests.

For a better understanding of the compaction mechanisms and the workability of asphalt mixtures, various intelligent compaction techniques have been introduced [8–10]. One of the most recent solutions is based on the use of particle-size sensors, which consist of an external shell and an internal wireless module capable of measuring acceleration,

^{*} Corresponding author.

E-mail addresses: o.guazzaroni@pm.univpm.it (O. Guazzaroni), l.p.ingrassia@pm.univpm.it (L.P. Ingrassia), a.virgili@univpm.it (A. Virgili), a.graziani@univpm.it (A. Graziani), f.canestrari@univpm.it (F. Canestrari).

<https://doi.org/10.1016/j.measurement.2026.123104>

Received 11 May 2026; Received in revised form 24 August 2026; Accepted 3 September 2026

Available online 4 September 2026

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rotation, and temperature, with the collected data transmitted in real time to a digital device via Bluetooth. The acceleration and rotation data are the ones of most interest in asphalt mixtures workability evaluation, whereas temperature remains a less used parameter because temperature is a controlled variable in laboratory testing. In addition, the temperature measured by the sensor is affected by the presence of the external shell, which makes the measurements lag behind the actual temperature of the mixture due to the time necessary for heat transfer [11]. The external shell of the sensor is typically produced by a 3D printer using a high-temperature-resistant, high-strength thermoplastic polymer, such as acrylonitrile butadiene styrene (ABS) with nylon, which was found to have good compatibility with asphalt materials [12].

In the field of civil engineering, these sensors were first applied to track the movement of railway ballast particles [13,14]. This technology was then employed in asphalt mixture research to investigate the kinematics of coarse aggregate particles during gyratory compaction [12]. Recognizing the particle-size sensors' effectiveness in characterizing asphalt mixture compaction, their use was standardized for pavement engineering applications by ASTM D8541 [15].

Although the ASTM D8541 standard suggests the use of 27 mm cubic sensors, studies in this field have also employed other sensor geometries, such as parallelepiped [16], spherical [17,18] or irregular shapes [19–21] to better simulate, in this latter case, the shape of a real coarse aggregate. Another important aspect is the sensor nominal size and the ratio between sensor nominal size and nominal maximum aggregate size (NMAS) of the asphalt mixture. A recent analysis of the literature [18] has shown that particle-size sensors with different nominal sizes have been used in laboratory experiments with gyratory compactors, with typical values of the ratio between sensor size and mixture NMAS ranging from 1 to 3. In general, this ratio can affect the measurements, as excessively high values may prevent the surrounding aggregates from inducing significant sensor movement and may even cause the sensor itself to partially compromise the local compaction degree.

Particle-size sensors were employed to investigate the impact of compaction temperature and Warm Mix Asphalt additives on mixture workability [22,23], and to analyze the effect of aggregate size and gradation [24]. They were also proposed for evaluating compaction of cold recycled mixtures [25] and unbound materials used in base layers [26,27]. Other studies [17,18] also correlated the workability parameters obtained from particle-size sensors with the compaction energy index (CEI) [28]. In one study, particle-size sensors were also embedded in slabs compacted with a roller pneumatic tyre compactor [5], revealing that this compactor exerted a more pronounced kneading action on the asphalt mixture than that observed in gyratory compaction.

The literature review shows that several studies have employed particle-size sensors during laboratory compaction. However, since laboratory compaction devices are inherently dynamic systems, their operation involves movements of the mold, and none of these studies have investigated in detail how such movements may influence sensor measurements. Similarly, the ASTM D8541 standard focuses on interpreting the motion of a particle-size sensor embedded within the gyratory compactor mold, assuming that the recorded signal reflects only the internal kinematics of the asphalt mixture. However, this assumption neglects the fact that the mold itself undergoes a rigid-body motion during compaction. As a consequence, the sensor output may be influenced by both the internal particle-size sensor movement and the rigid motion of the mold. Prior studies have shown that, even when two compactors conform to the same standard, differences in their compaction mechanisms can significantly influence the sensor measurements [18]. This highlights the importance of considering machine-specific characteristics when interpreting sensor data and comparing results across laboratories.

On the other hand, the application of particle-size sensors in laboratory roller compaction has not been thoroughly explored and

standardized. Although both gyratory compactor and roller compactor are designed for laboratory compaction of asphalt mixtures, their operating principles differ substantially. As a result, combining laboratory roller compaction with embedded particle-size sensors requires further investigation to ensure reliable measurements. Moreover, since roller compaction is the laboratory method that best reproduces the field compaction mechanism, a deeper investigation of particle-size sensors could offer valuable insights into field compaction processes as well.

Overall, the literature reveals several unresolved gaps: the influence of mold kinematics on ASTM D8541 workability parameters has not been systematically assessed; the extent to which sensor measurements reflect true aggregate motion versus rigid mold movement remains unclear; and the application of particle-size sensors in laboratory roller compaction lacks an established methodological framework.

Based on these considerations, the first objective of this study is to provide a critical assessment of the ASTM D8541 workability parameters for the gyratory compactor, examining whether they can be consistently applied across different gyratory compactor models and how mold kinematics affect their interpretation. The second objective is to explore the feasibility of applying particle-size sensors in laboratory steel-roller compaction, where no consolidated framework currently exists. To pursue these aims, two gyratory compactors, one steel roller compactor, three asphalt mixtures, an unbound granular material, and two sensor geometries (spherical and cubic) were considered. A novel workability parameter is introduced to overcome the limitations of the existing ASTM D8541 indices and to provide a locally measured indicator of compaction behaviour.

2. Materials and methods

2.1. Asphalt mixtures and unbound granular material

The experimental program included the investigation of a dense-graded base course (DGBC), a dense-graded friction course (DGFC) and an open-graded friction course (OGFC). They were selected to represent a range of gradations, binder contents, and reclaimed asphalt pavement (RAP) contents (Fig. 1 and Table 1). All mixtures were produced at the asphalt plant and re-heated in the laboratory for three hours at the compaction temperature of 160 °C. The DGBC and OGFC mixtures were produced with a polymer-modified bitumen (PMB), containing about 4% of SBS (styrene-butadiene-styrene) radial polymers, whereas the DGFC mixture contains 50/70 neat bitumen. An unbound granular material, with the same particle size gradation of OGFC, was also included in the experimental program to investigate the influence of temperature and material type on the rigid movement of the mold.

2.2. Particle-size sensors

The particle-size sensors consist of an internal measurement unit housed within a protective external shell. The internal unit is based on the WT901BLE multi-sensor module by WitMotion, which integrates the MPU9250 MEMS system combining a three-axis accelerometer, a three-axis gyroscope, a three-axis magnetometer and a temperature sensor. This module can record accelerations, angular velocity, angles, magnetic field and temperature at sampling frequencies up to 50 Hz. It is supplied with factory firmware that enables communication with either a computer or a smartphone through Bluetooth. For improved robustness and handling, the WT901BLE module was mounted on a custom-designed printed circuit board. Thanks to its low power demand, the system was powered by a CR2032 lithium primary cell.

The module has a local reference system (x, y, z), based on which it provides measured parameters. However, as suggested by the ASTM D8541 standard, the parameters must be converted to the global reference system (X, Y, Z) characterized by a vertical Z-axis before proceeding with workability analyses.

The sensor can operate using a 6-axis algorithm or, alternatively, a 9-

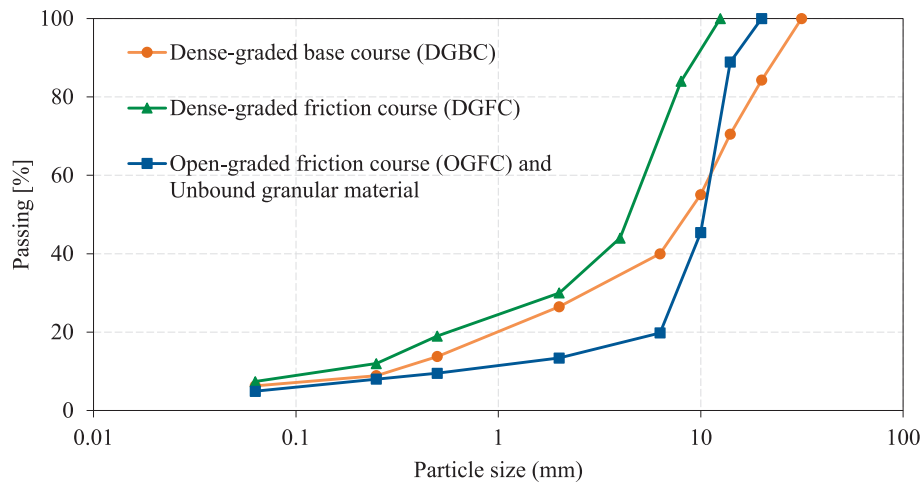


Fig. 1. Gradation curve of the studied asphalt mixtures.

Table 1
Characteristics of the studied asphalt mixtures.

Mixture	Binder type	Binder (by aggregate weight) [%]	RAP (by aggregate weight) [%]	NMAS [mm]
Dense-graded base course (DGBC)	PMB 45/80–70	4.4	30	20
Dense-graded friction course (DGFC)	50/70 pen	5.2	–	8
Open-graded friction course (OGFC)	PMB 45/80–70	5.4	25	14

axis algorithm configuration. In the 6-axis setup, the z-angle is mainly calculated based on the angular velocity integral, whereas, in the 9-axis setup, the z-angle is calculated based on the Earth's magnetic field. Since the sensor is inserted inside a steel mold during compaction, there is significant magnetic field interference in the installation environment. For this reason, the sensor was configured to operate with the 6-axis algorithm to obtain a more accurate z-angle.

Two alternative external shells, a spherical and a cubic version, were

developed for the device (Fig. 2). The spherical shell, with a diameter of 35 mm, is composed of two halves joined through four tongue-and-groove connectors, whereas the cubic shell, with a side length of 31 mm, is assembled using four screws. These shells were made of a selected resin and produced through stereolithography 3D printing technology. The external surfaces of the shells are covered with spherical caps with a base radius of 2.2 mm and a height of 1 mm, in order to enhance interlocking during the compaction process. Both casings are reusable and were designed to fulfill three main functions: to replicate the size and behavior of a coarse aggregate within the asphalt mixture, to protect the sensor from the temperatures and stresses applied during the compaction process, and to ensure adequate Bluetooth communication between sensor and smartphone [17,18].

The ratios between the nominal sensor size and the NMAS of the DGBC, DGFC, and OGFC mixtures are 1.8, 4.4, and 2.5 for the spherical sensor, and 1.6, 3.9, and 2.2 for the cubic sensor, respectively. The DGFC mixture was specifically selected for its fine aggregate gradation to assess the effect of a high ratio between sensor size and mixture NMAS on the sensor measurements. Fig. 3 shows that the coarse aggregates of the DGBC mixture are fully comparable in size to the spherical sensor (and thus to both shells), making the use of the developed sensors entirely appropriate and consistent with the material's aggregate scale.

Prior to each test, sensor auto-calibration [18] is performed to ensure

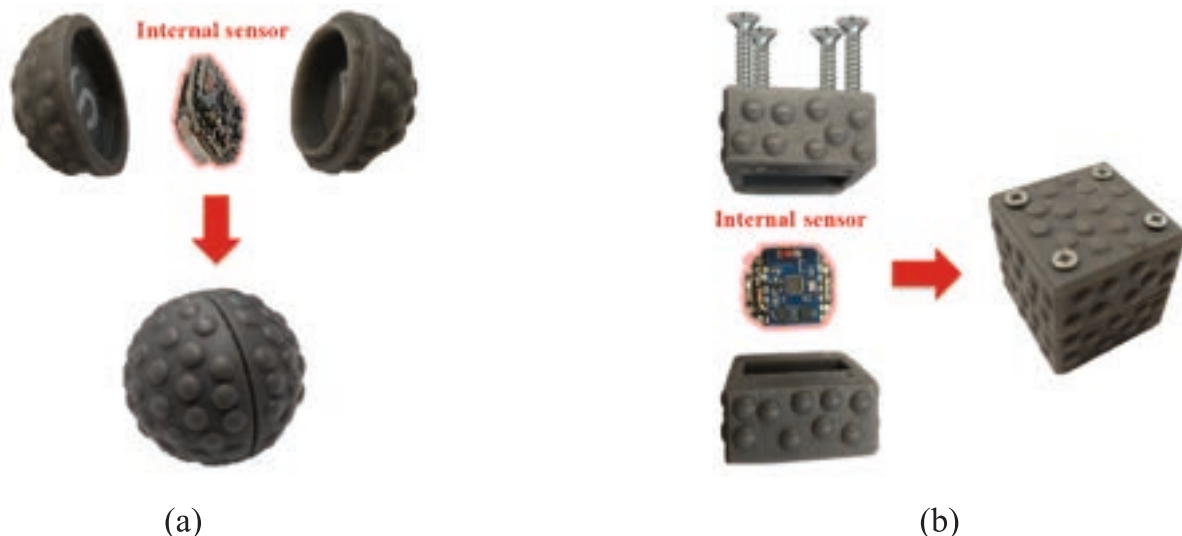


Fig. 2. Particle-size sensors: (a) spherical; (b) cubic.



Fig. 3. Comparison between the spherical sensor and coarse aggregates from the DGBC mixture.

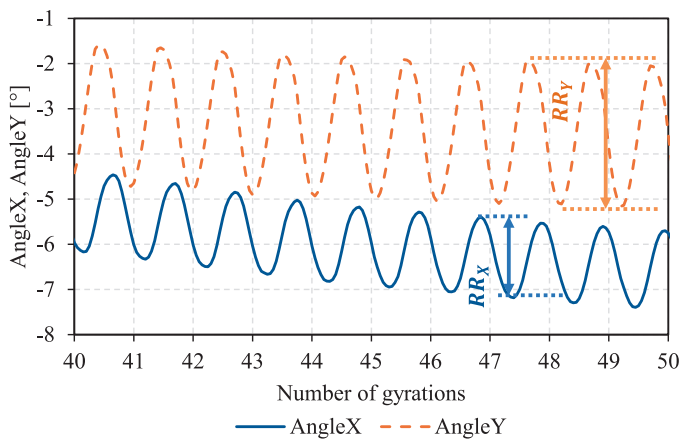
a clearer and more readily interpretable output. The auto-calibration procedure aligns the local reference system of the sensor with the global reference system. This alignment enables the acquisition process to begin from a null kinematic configuration, meaning that all three Euler angles are initialized to zero at the start of the test, thereby allowing the recorded data to reflect the motion generated by the sensor during the compaction process, with reference to the global system. However, in the few seconds between the auto-calibration and the start of the compaction, the sensor may move due to minor material rearrangement. For this reason, during post-processing, the Euler angles are re-converted to the global coordinate system using quaternion-based rotation matrices derived from the data collected in the short interval between the sensor auto-calibration and the beginning of compaction.

ASTM D8541 has defined procedures to evaluate the workability of asphalt mixtures during gyratory compaction by means of relative rotations (RR) measured by particle-size sensors. The relative rotation at a specific cycle is defined as the difference between the peak and valley value of the Euler angle in the global coordinate system (Fig. 4a). The ASTM standard suggests averaging the relative rotations at horizontal X- and Y-directions for workability analysis.

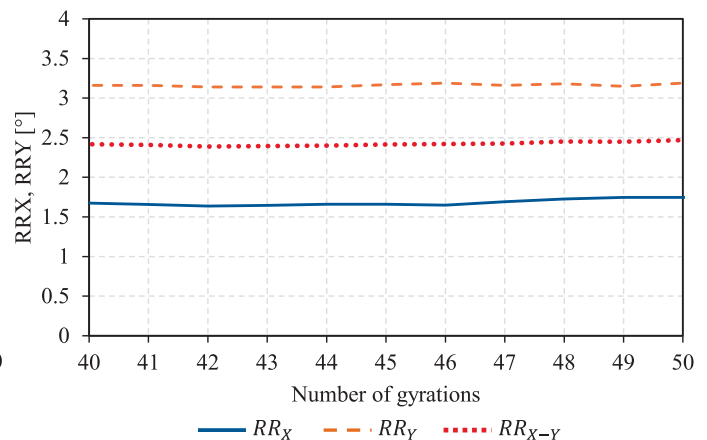
The relative rotation capacity (RRC) is then calculated as the area under the average RR curve (RR_{X-Y}) (Fig. 4b):

$$RRC = \sum_{i=N_i}^{N_d} \frac{(RR_{i+1} + RR_i) \cdot l}{2} \quad (1)$$

where N_i is the initial number of gyrations; N_d is the design number of gyrations; RR_i and RR_{i+1} represent the relative rotations at the i^{th} and $(i + 1)^{th}$ gyration, respectively; l refers to the x-axis unit (one



(a)



(b)

Fig. 4. ASTM D8541 workability parameters: (a) Euler angles at horizontal directions (global reference system); (b) Relative rotations (RR).

compaction cycle). According to ASTM D8541, a higher value of RRC denotes a more active particle rotation and thus better workability.

2.3. Gyratory compaction

Gyratory compaction is characterized by the simultaneous application of static axial compression and shear stresses to the mixture. The equipment models used in this study are B100B92 by Tecnotest (compactor A) and Gyrocomp by IPC GLOBAL (compactor B) (Fig. 5). They both operate following the test conditions defined by the EN 12697-31 [29] standard: rotational speed of 30 rpm, vertical pressure of 600 kPa, external angle of inclination of 1.25°. However, the two gyratory compactors are characterized by different working mechanisms. Gyratory compactor A (Fig. 6a) induces compaction through a rigid circular motion of the bottom surface of the mold, which generates a conical surface of revolution, whereas gyratory compactor B (Fig. 6b) is characterized by the rotation of the entire system (mold, specimen and loading plates) around its inclined axis. In both cases, the top and bottom surfaces of the specimen remain perpendicular to the vertical axis, even if the mold axis is tilted.

The experimental tests conducted using gyratory compactors included an initial investigation of the influence of the equipment type on the measured workability parameters. In particular, the mold movement of the gyratory compactors was investigated by placing a sensor to the external surface of the mold during compaction (Fig. 5). The sensor was positioned so as not to interfere with the contact points between the mold and the equipment: in gyratory compactor A it was mounted near the base of the mold, whereas in gyratory compactor B it was mounted at mid-height. According to rigid-body kinematics, all points of a rigid body undergo the same angular displacement, angular velocity, and angular acceleration during rotation; therefore, the specific location of the external sensor does not influence the angular measurements being investigated. The mold movement was examined with two materials. First, 3900 g of OGFC were compacted at 160 °C, then 3000 g of unbound granular material were compacted at 20 °C. These contrasting configurations were selected to explore whether variables such as temperature, material mass, and material type could influence the rigid movement of the mold. Each condition was evaluated through two replicate compaction tests.

After the analysis of the mold motion, the workability of the three asphalt mixtures (Table 1) was evaluated with embedded spherical particle-size sensor using gyratory compactor A. The spherical sensor (Fig. 2a) was inserted at mid-depth position in the 150 mm mold, as this is the optimal position for observing the aggregate movement [12,13]. All compaction tests were performed up to 100 gyrations. The mass of

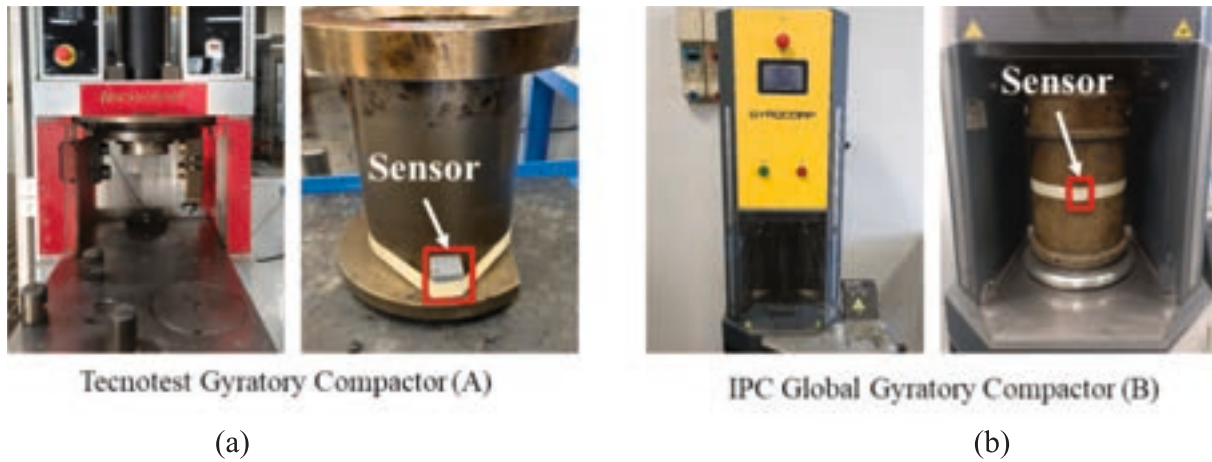


Fig. 5. Gyratory compactors and positioning of the sensor on the external surface of the gyratory molds: (a) Gyratory compactor A; (b) Gyratory compactor B.

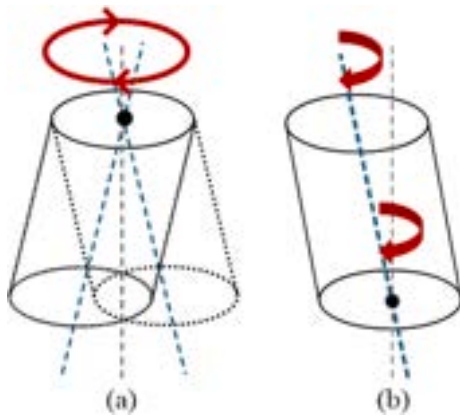


Fig. 6. Gyratory compactor mechanism: (a) Gyratory compactor A, (b) Gyratory compactor B.

the specimens was determined to obtain an approximate height of 115 mm for all mixtures, resulting in a mass equal to 4800 g for the DGBC mixture, 5000 g for the DGFC mixture, and 3900 g for the OGFC mixture. As suggested by ASTM D8541, approximately half of the mixture was placed into the 150 mm mold, previously kept in the oven for at least 45 min at the compaction temperature of 160 °C, trying to create a flat surface, and the sensor was placed in the center with its z-axis aligned with the vertical direction. The remaining material was finally poured into the mold.

The air void content of the compacted specimens was calculated based on EN 12697-8 [30]. The bulk density was calculated based on EN 12697-6 [31] (by dimensions), by subtracting the mass and the volume of the particle-size sensor from those of the mixture.

The compaction energy index (CEI) was also calculated. CEI is defined as the area under the compaction curve from the 8th gyration until a compaction degree of 92% for dense-graded mixtures [28] and 80% for open-graded mixture [32], with high CEI values indicating low mixture workability and vice versa.

Regarding the RRC parameter proposed by ASTM D8541 (Eq. (1)), consistently with the definition of CEI, N_i was assumed to be equal to 8, while N_d was taken as the number of gyrations corresponding to a compaction degree of 92% for dense-graded mixtures and 80% for the open-graded mixture.

2.4. Roller compaction

The steel roller compactor consists of a parallelepiped steel mold that

moves back and forth, and a steel roller. The compaction process was performed with Roller sector compactor 30 kN by Infratest (Fig. 7), based on EN 12697-33 [33]. The steel roller, characterized by a segment radius of 550 mm, applies a variable load during compaction (Fig. 8). Following the height-controlled procedure, compaction begins with a first phase at height control, after which the load is reduced to zero. Then, the main compaction phase begins, consisting of the initial levelling of the mixture followed by the actual compaction under height control, until the target height is reached. A target height of 100 mm was fixed to ensure adequate thickness both above and below the sensor, in order to prevent its damage and to achieve a slab thickness of at least 3 times the size of the sensor shell.

The movement of the mold was investigated by placing a sensor to its external surface, close to the base (Fig. 9). The mold was filled with 22900 g of OGFC at 160 °C or with 15000 g of unbound granular material at 20 °C, for the same reasons described for the gyratory compactor (Section 2.3).

After the analysis of the mold motion, the three asphalt mixtures (Table 1) were compacted with both spherical and cubic particle-size sensors embedded and placed exactly at the center of the slabs [5]. This allowed to limit the stress transmitted to the sensor and thus ensured its reusability. Fig. 10 shows the preparation of the slabs. First, half of the material was poured into the mold, trying to achieve an even surface. The sensor was placed at the center with its z-axis aligned with the vertical direction and the x-axis corresponding to the compaction direction. Finally, the remaining material was poured. As for gyratory compaction procedure, sensor auto-calibration was performed before starting the roller compaction.

Slabs measuring 400 mm (length, L_1) $\times$ 300 mm (width, L_2) $\times$ 100 mm (height, h) were compacted by setting a target height corresponding to an air void content of 8% for the DGBC mixture, 10% for the DGFC mixture and 24% for the OGFC mixture. For all mixtures, a load lower than 20 kN was applied during compaction. Such load levels prevented any damage to the sensors, thus allowing their reuse in subsequent compaction tests. The air void content of the compacted slabs was calculated determining bulk density by dimensions by subtracting the mass and the volume of the particle-size sensor from those of the mixture.

Since the roller compaction process is cyclic, it is possible to determine the corresponding relative rotation related to horizontal directions (RR_x , RR_y) using the same approach described by ASTM D8541 for gyratory compaction. A cycle is defined as a rolling passage (back and forth movement of the steel roller). Consequently, it is also possible to calculate the RRC parameter using Eq. (1) and assuming that RR_i is the relative rotation at i^{th} rolling passage, RR_{i+1} is the relative rotation at $(i+1)^{th}$ rolling passage, l refers to the x-axis unit (one rolling passage),



Fig. 7. Roller compactor by Infratest.

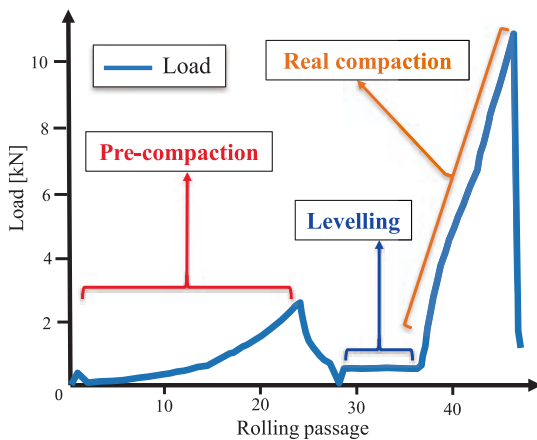


Fig. 8. Roller compaction load following height-controlled procedure.

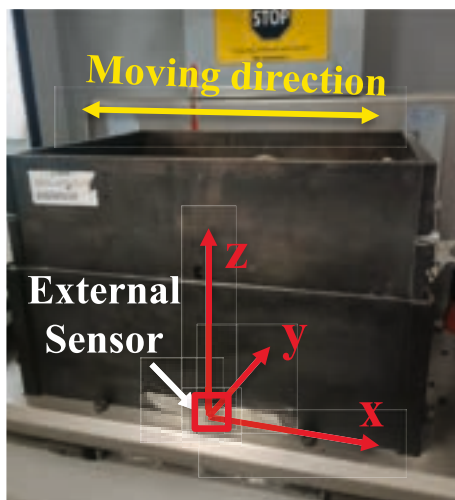


Fig. 9. Positioning of the sensor on the external surface of the roller steel mold.

N_i is the first effective rolling passage (see Section 3.4), N_d is the total number of rolling passages until the target height of 100 mm is reached.

2.5. Experimental program

The experimental program (Table 2) involved the mold motion investigation of the two gyratory compactors and the roller compactor using two different materials (OGFC and unbound granular material). The workability of the three asphalt mixtures (Table 1) was studied using gyratory compactor A with the spherical sensor embedded and using the roller compactor with both spherical and cubic sensors embedded. Two replicate specimens were considered for each combination.

Hereafter, the specimens are coded according to a 3-part nomenclature, such as “DGBC_RC_S1”, where the first part indicates the mixture type (DGBC, DGFC or OGFC), the second part indicates the compaction method (“RC” for roller compaction or “GC” for gyratory compaction) and the last part indicates sensor shell geometry (“S” for spherical, “C” for cubic) and the replicate specimen number.

3. Results and analysis

3.1. Gyratory mold motion

Fig. 11 and Fig. 12 illustrate the Euler angles and the corresponding relative rotations (RR) recorded by the sensor placed outside the mold, containing different materials (OGFC at 160 °C and unbound granular material at 20 °C), for gyratory compactor A and gyratory compactor B, respectively. It is possible to observe that the Euler angles recorded for the same gyratory compactor but with different materials exhibit identical trends. The vertical shift among the Euler angle curves is due to the initial test configuration, specifically the position of the sensor on the mold. In fact, when the gyratory compaction test begins, the gyratory angle is applied to the mold. This initial application of the gyratory angle occurs along a defined direction. Therefore, if the sensor is not positioned in exactly the same position in repeated tests, the initial application of the gyratory angle produces a slightly different initial rotation of the sensor each time. This effect is the cause of the vertical shift observed among the Euler angle curves. The relative rotations remain constant when considering the same gyratory compactor, whereas differences are observed when comparing gyratory compactors A and B. In summary, the relative rotation associated with the rigid-body movement of the gyratory mold can be considered as a property of the equipment, as it was not affected by temperature, material mass, or material type.

Theoretically, the RR value should be two times the external gyratory angle (1.25° based on EN 12697-31 [29]). Differences between what was measured (2.35° and 3.00° for gyratory compactors A and B,

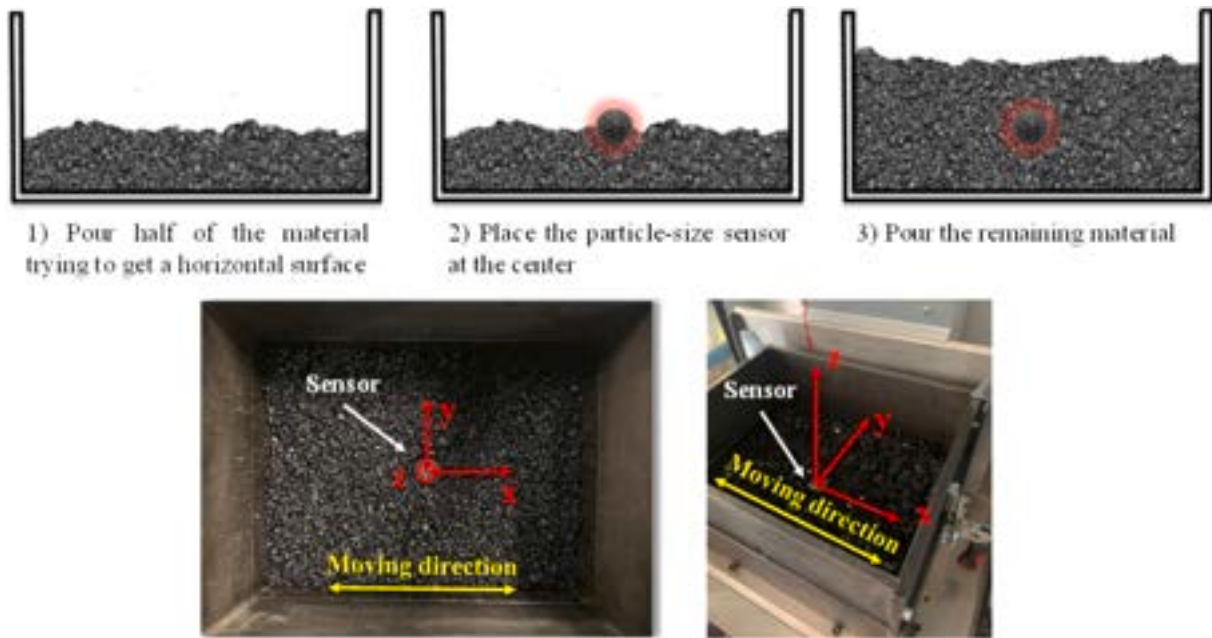


Fig. 10. Slab preparation and sensor orientation in roller compaction tests with embedded sensor.

Table 2
Experimental program.

	Gyratory compactor A	Gyratory compactor B	Roller compactor
Mold motion investigation	X	X	X
Three asphalt mixtures + Spherical sensor	X		X
Three asphalt mixtures + Cubic sensor			X

respectively) and what was expected to be measured (2.50°) could be caused by the different working mechanisms of the equipment (Fig. 6), but it could be also related to their calibration. Fig. 11 and Fig. 12 additionally report the variances associated with the RR measurements, which arise from sensor calibration, Bluetooth transmission, sensor drift, and intrinsic MEMS measurement accuracy.

Rigid movement of the mold can vary depending on the compactor mechanism. Therefore, the workability parameters proposed by ASTM D8541 cannot be uniformly applied across machines. Since the computation of RRC involves placing the sensor inside the mold (i.e., in a dynamic environment), its motion and thus the calculated RRC value must be corrected by subtracting a fixed amount corresponding precisely to the rigid movement of the mold. Therefore, initial calibration tests are required to characterize and thoroughly consider the specific mold motion. These observations suggest that ASTM D8541 should include machine-specific recommendations depending on the gyratory compactor model employed.

3.2. Gyratory compactor results

Fig. 13 illustrates the gyratory compaction curves and the N_d values obtained for the three asphalt mixtures, each evaluated through two replicate specimens. A comparison between the dense-graded mixtures shows that DGFC exhibits better compaction from the very beginning, ultimately achieving a lower final air void content than DGBC. Table 3

reports the air void content of the gyratory-compacted specimens at 100 gyrations. When comparing the dense-graded mixtures, the DGFC mixture shows lower N_d and air void values than DGBC, confirming its higher compactability under identical compaction conditions.

Fig. 14 illustrates relative rotations at horizontal directions (RR_X , RR_Y) and their average (RR_{X-Y}) obtained with gyratory compactor A and the spherical sensor. The graphs also show the RR_{mold} value (2.35°) recorded for gyratory compactor A (Fig. 11). It is noteworthy that the RR_{X-Y} values are always lower than the RR_{mold} value, associated with the movement of the mold. In addition, after a certain number of gyrations, RR_{X-Y} approaches the RR_{mold} value, suggesting that, for high levels of compaction, RR_{X-Y} would converge exactly to RR_{mold} . In the hypothetical situation of a perfectly compacted mixture, RR_{X-Y} should be equal to RR_{mold} .

Fig. 15a shows the RRC values at horizontal directions (RRC_X and RRC_Y) for the DGBC, DGFC and OGFC mixtures. The observed differences among the two directions are likely caused by the heterogeneity of the mixture and, in particular, by the material surrounding the sensor. For example, the presence of coarse particles near the sensor may hinder motion in that direction but not in the others. According to ASTM D8541, the RRC values averaged over the horizontal directions should be used to evaluate mixture workability. Since higher RRC values should indicate greater aggregate mobility and therefore good workability, the results would suggest that the DGBC mixture exhibits better workability than the DGFC mixture.

Fig. 15b shows the CEI values for all tests performed. It can be observed that CEI values are similar across tests performed on the same mixture. Moreover, this parameter appears to differentiate between the two mixture types. Since lower CEI values indicate better workability, the results suggest that the DGFC mixture exhibits better workability than the DGBC mixture, probably due to the different NMAS value of the two mixtures (see Table 1). In fact, the DGFC mixture is a very fine mixture (NMAS = 8 mm), which achieves 92% degree of compaction at a lower number of gyrations than the DGBC mixture (Fig. 13) and thus does not require very high compaction energy. Instead, the CEI definition for open-graded mixtures is different, as the CEI index considers the compaction process up to an air void content of 8% for dense-graded mixtures and 20% for open-graded mixtures. Therefore, the results obtained for the OGFC mixture are not directly comparable to those of the other mixtures.

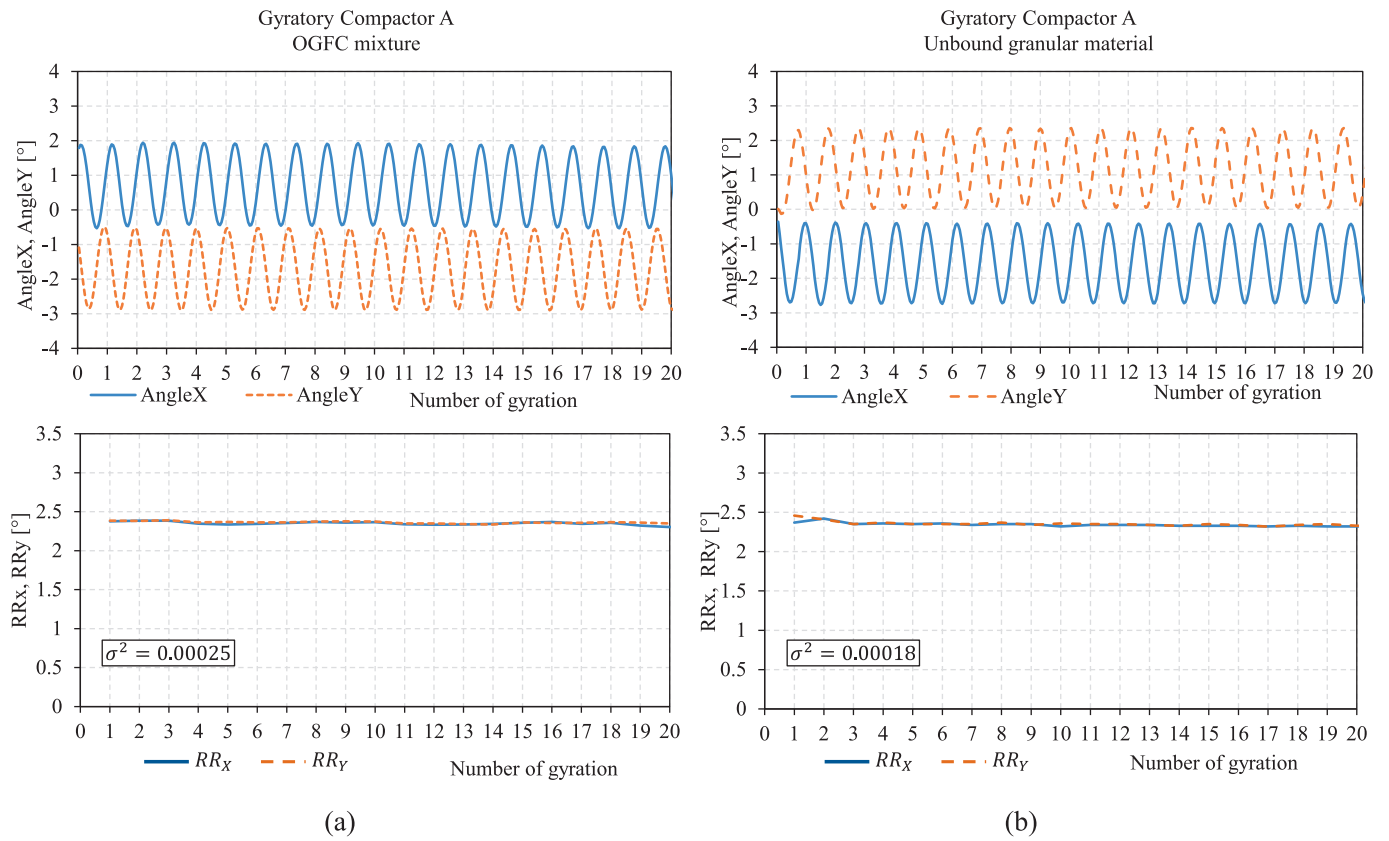


Fig. 11. Euler angles at horizontal directions and relative rotations measured by external sensors for gyratory compactor A and different materials: (a) OGFC mixture, (b) Unbound granular material.

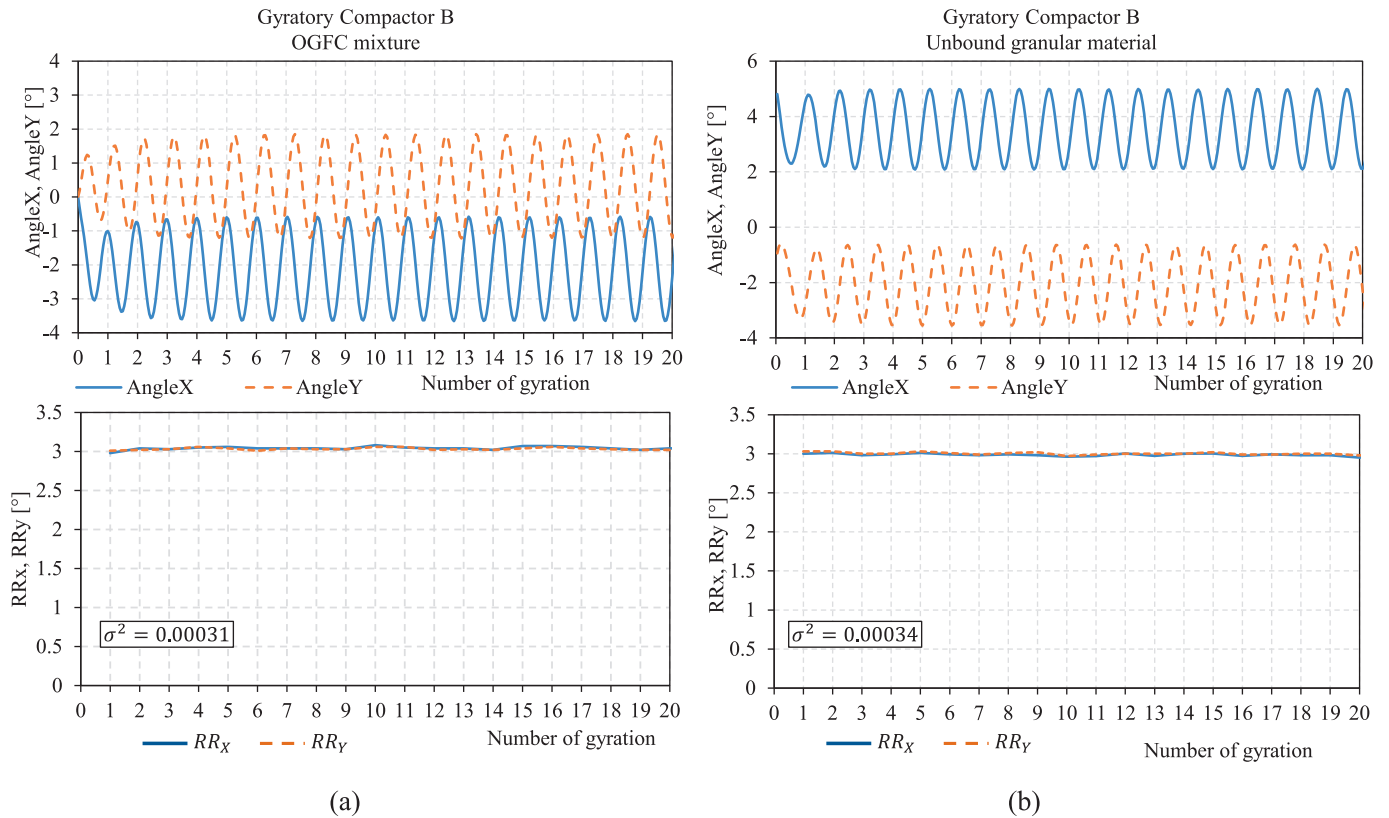


Fig. 12. Euler angles at horizontal directions and relative rotations measured by external sensors for gyratory compactor B and different materials: (a) OGFC mixture, (b) unbound granular material.

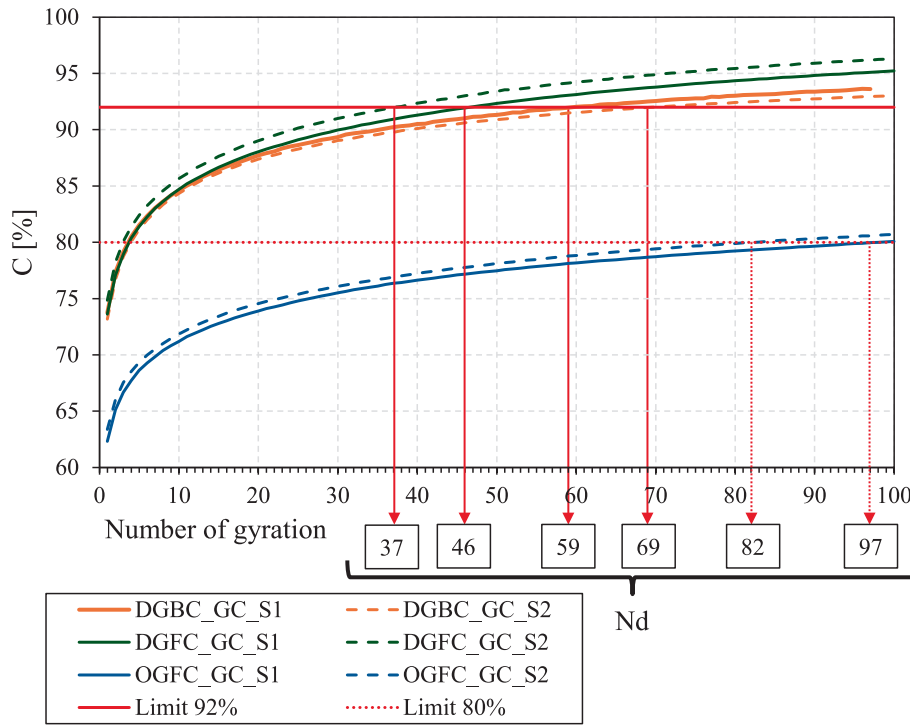


Fig.13. Gyratory compaction curves obtained for the three asphalt mixtures.

Table 3

Air void content for all gyratory compactor specimens at 100 gyrations.

Specimen ID	DGBC_GC_S1	DGBC_GC_S2	DGFC_GC_S1	DGFC_GC_S2	OGFC_GC_S1	OGFC_GC_S2
Air void content [%]	5.7	7.0	4.8	3.6	19.9	19.3

The RRC values averaged over the horizontal directions for the dense-graded mixtures are compared with the CEI values in Fig. 16. There appears to be direct proportionality between the two parameters. As outlined above, this behaviour contradicts the meaning attributed to each parameter, as high RRC values, indicating good workability, correspond to high CEI values, indicating poor workability. This inconsistency raises questions about the data interpretation proposed by the ASTM D8541 standard, also because the results shown in Fig. 11 and Fig. 12 indicate that the motion of the mold: a) is not the same for different compactors and b) affects the RRC value.

Based on the previous observations, the mixture movement during gyratory compaction and the forces acting on it were re-evaluated. Fig. 17 schematizes the forces exerted on the mixture during compaction [34]. The gyration angle (δ) causes a nonuniform distribution of pressure on the top and bottom plates of the mold [35]. The resultant (V) of the vertical pressure is therefore misaligned by an eccentricity (e). This generates a shear force (F_g), affected by tangential forces (F), that produces a tilting moment ($M = V \bullet 2e$) on the specimen, acting in the direction opposite to δ . Therefore, the rotation induced by M is partially compensated by the rotation associated with the rigid-body motion of the mold. This interaction occurs cyclically in radial direction during compaction.

Therefore, to evaluate the actual relative motion between the mold and the sensor, it is necessary to define a novel workability parameter able to take into account that the rotations caused by the tilting moment and those induced by the rigid motion of the mold have opposite signs. This novel parameter, called *Mold-Sensor Relative Rotation Capacity* (M-S RRC), is defined as the area between the RR_{mold} and RR_{X-Y} curves, as follows:

$$M-S RRC = \sum_{i=N_d}^{N_d} \left| \frac{(RRx - y_{i+1} + RRx - y_i)}{2} - RR_{mold} \right| \bullet l \quad (2)$$

where $RRx - y_i$ is the average relative rotation of the compacted asphalt mixture at i^{th} gyration, $RRx - y_{i+1}$ is the average relative rotation of the compacted asphalt mixture at $(i+1)^{th}$ gyration, RR_{mold} is the relative rotation of the rigid motion of the mold (2.35° for gyratory compactor A, see Fig. 11), l is the length of the x-axis unit (one compaction gyration). As explained in Section 2.3, N_i was assumed equal to 8, whereas N_d corresponded to the number of gyrations associated with a compaction degree of 92% for dense-graded mixtures and 80% for the open-graded mixture, consistently with the CEI definition (see Fig. 13).

Fig. 18 shows how the RRC and M-S RRC values for all mixtures are determined. The figure suggests that high RRC merely indicates that the sensor moves as the mold, without any actual relative mold-sensor motion. On the other hand, high sensor mobility is well represented by the proposed parameter (M-S RRC), which better captures the relative motion between sensor and mold and thus provides information regarding the actual compaction of the mixture. Specifically, the higher the M-S RRC parameter, the greater the sensor movement relative to the mold, which may indicate a lower workability. This evidence further undermines the validity of the ASTM D8541 assumption that a high RRC value reflects substantial sensor movement.

Fig. 19a compares the M-S RRC values for the DGBC, DGFC and OGFC mixtures. Comparing dense-graded mixtures, the DGFC mixture shows lower values of M-S RRC than DGBC, as it tends to achieve a high level of compaction rapidly due to its low energy requirements for compaction. The low M-S RRC values for the DGFC mixture may also be related to the high ratio between the sensor nominal size and the NMAS

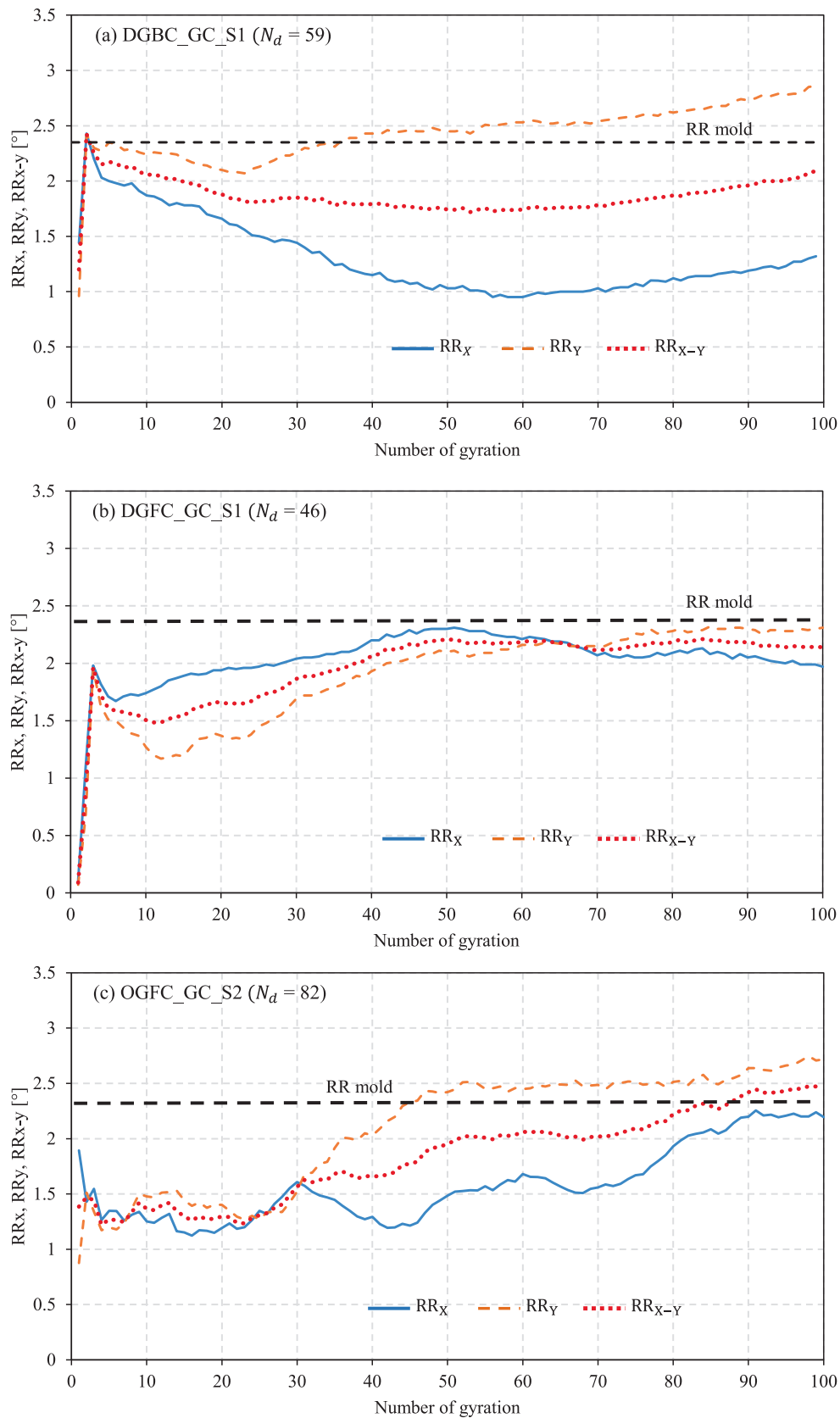


Fig.14. RR related to horizontal directions (x and y) and average x-y RR for gyratory compaction tests for three asphalt mixtures: (a) DGBC_GC_S1 specimen, (b) DGFC_GC_S1 specimen, (c) OGFC_GC_S2 specimen.

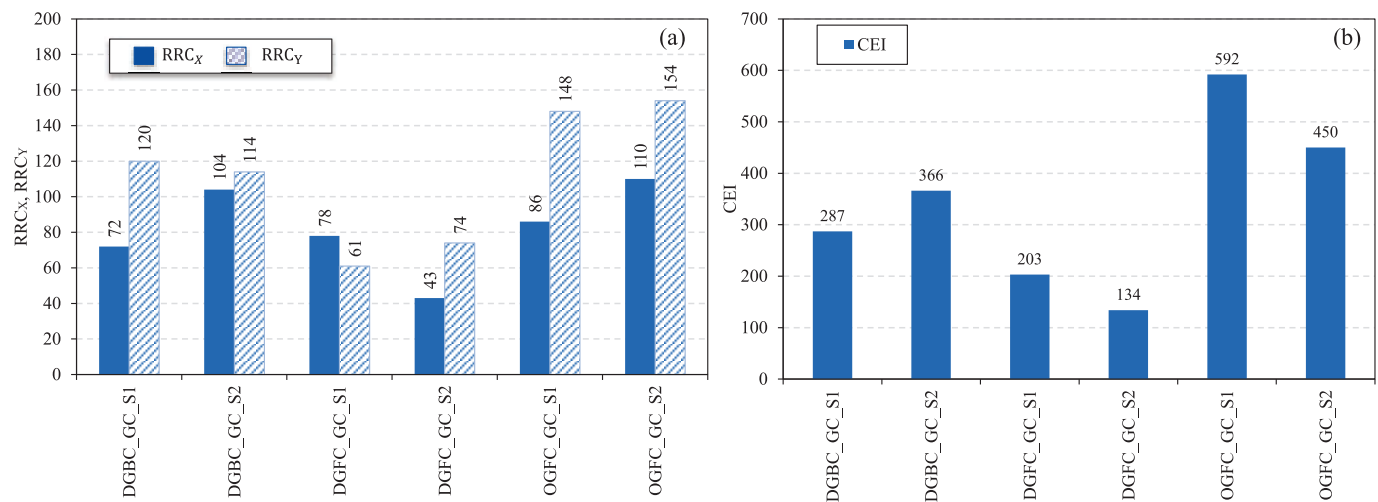


Fig. 15. Workability parameters for gyratory compaction tests related to three asphalt mixtures: (a) RRC_x and RRC_y (ASTM D8541); (b) CEI.

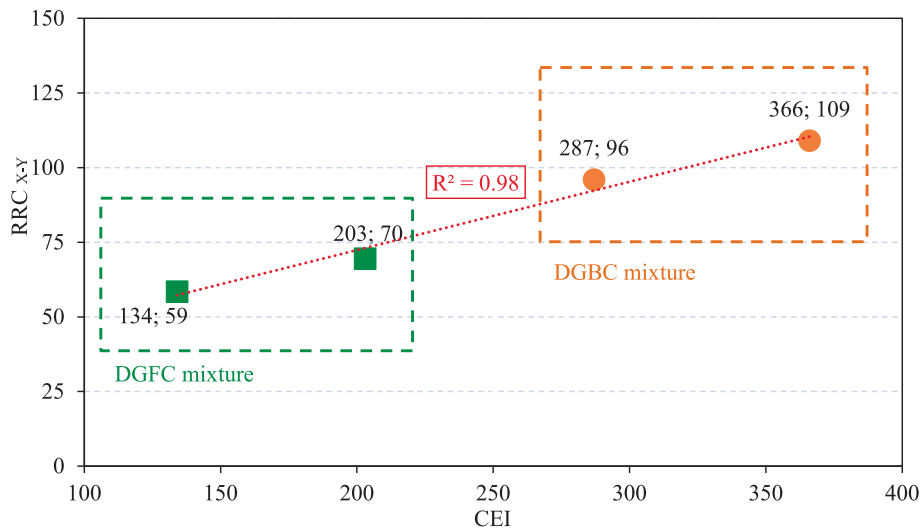


Fig. 16. Average RRC values vs. CEI related to dense-graded mixtures.

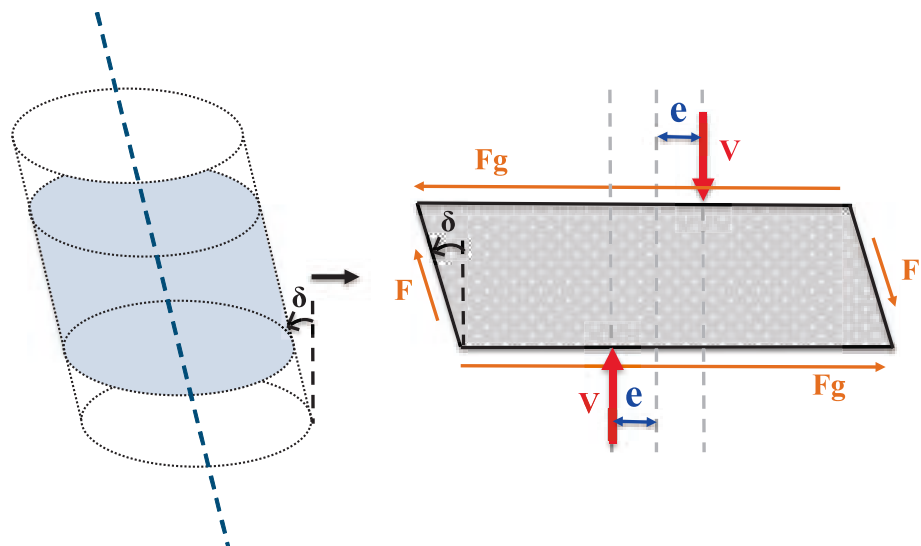


Fig. 17. Gyratory specimen under compaction configuration and free body diagram of the forces acting on specimen.

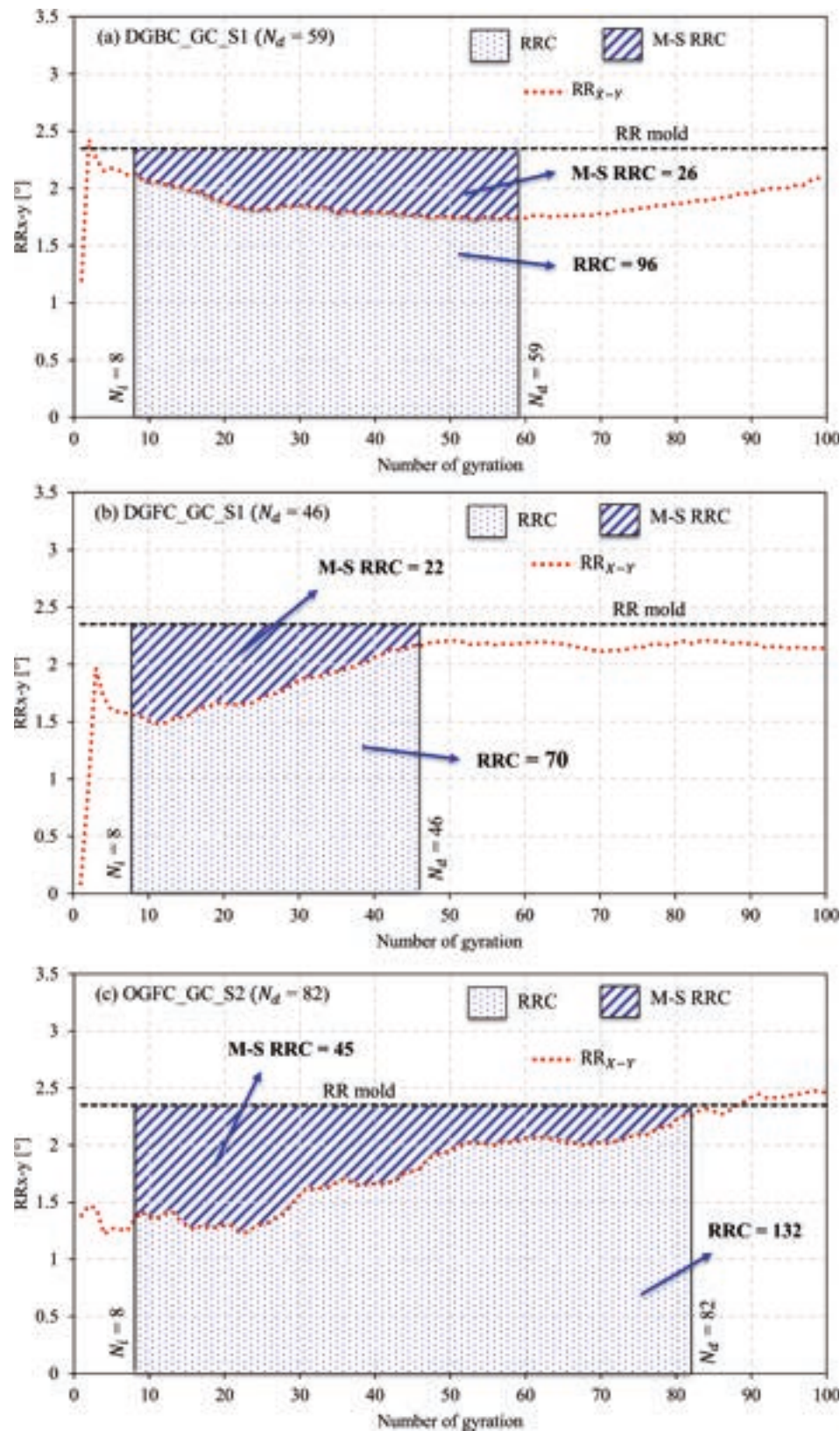


Fig. 18. RRC and M-S RRC values for three asphalt mixtures: (a) DGBC_GC_S1 specimen, (b) DGFC_GC_S1 specimen, (c) OGFC_GC_S2 specimen.

(4.4). In fact, the aggregates surrounding the sensor may be too small to induce any meaningful sensor movement.

The proposed parameter also shows a favorable indicative trend with the CEI parameter. Fig. 19b illustrates a clear direct proportionality

between the two, with M-S RRC increasing as CEI increases. In fact, both the CEI and M-S RRC parameters quantify the compaction energy needed to bring the asphalt mixture from an initial loose state (implying a relative motion between the sensor and the mold) to a final compacted

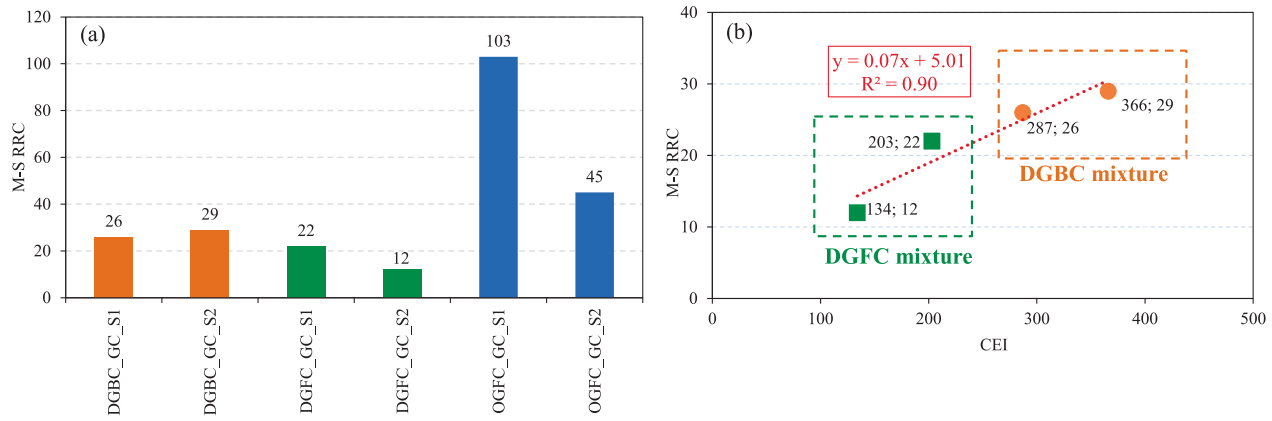


Fig. 19. Novel workability parameter for gyratory compaction: (a) M–S RRC values; (b) M–S RRC vs. CEI.

state (in which the sensor tends to move rigidly with the mold). The main difference between the two parameters is that the CEI refers to the gyratory specimen as a whole, whereas the M–S RRC value is derived from the data measured locally by the sensor. Despite the high sensor-to-NMAS ratio observed for the DGFC mixture, its behavior remains consistent with the correlation, demonstrating that the proposed parameter retains validity even for fine gradations.

In addition to the correlations already discussed, further relationships were explored using parameters previously determined from gyratory compaction. Fig. 20 presents the trend between the novel M–S RRC parameter and N_d . A clear direct proportionality is observed: mixtures that reach the isovolumetric condition at lower N_d values also exhibit lower M–S RRC values. Although such a trend may appear intuitive, it is not trivial, as compaction curves can exhibit markedly different shapes depending on mixture gradation, binder type and content. The consistency of this relationship further supports the physical interpretability of the proposed parameter and its ability to reflect the compaction effort required to densify the mixture.

3.3. Roller compactor mold motion

Fig. 21 shows the data recorded by the sensor fixed to the external surface of the mold in the case of OGFC at 160 °C in terms of Euler angles at horizontal directions, acceleration (AccX) along the compaction direction (X-axis) (Fig. 21a) and relative rotations at horizontal directions (Fig. 21b). The tests conducted with unbound granular material at 20 °C inside the steel mold yielded the same results in terms of rigid movement of the mold. Therefore, the rigid movement of roller steel mold can be considered as an intrinsic property of the equipment, as it was not affected by temperature, material mass, or material type.

The roller compactor requires approximately five seconds for each

cycle (back and forth from left to right), and before reversing direction it pauses for about half a second (“stop time” in Fig. 21a). The mold translation in the X-direction induces sensor rotations around the Y-axis. The mold movement appears to be predominantly translational along the X-axis (compaction direction), but small rotations, captured by the sensor, are also present. In fact, Fig. 21a illustrates that the X-axis Euler angle is negligible, whereas the Y-axis Euler angle follow a zero-mean quasi-sinusoidal pattern with a peak-to-peak amplitude of 1.70°.

By comparing the X-axis acceleration with the Y-axis Euler angle (Fig. 21a), it is possible to associate specific Euler angle values with distinct roller positions at fixed instants. Two acceleration peaks of the same sign are observed on the X-axis, separated by a “stop time”. The first peak corresponds to the deceleration required to stop mold motion, while the second peak reflects the acceleration needed to set it in motion again in the opposite direction. Three specific positions were identified and numbered from 1 to 3, as shown in Fig. 21c. Position 1 corresponds to the roller compactor to the left of the sensor, position 2 to the roller compactor directly above the sensor, and position 3 to the roller compactor to the right of the sensor. Position 2 coincides with the peaks of the periodic pattern of the Y-axis Euler angles (Fig. 21a). At the instant corresponding to position 2, the mold reverses its direction of rotation.

This behaviour can be explained considering that the roller compactor transmits compaction forces not only to the asphalt mixture but to the entire system that supports and moves the parallelepiped steel mold. The steel parallelepiped mold responds to the applied load by rotating in the direction of the load application, resulting in a cyclic and uniform rotational pattern throughout the compaction process. Such a cyclic movement remains constant throughout the compaction process and results in a constant relative rotation around the Y-axis (RR_Y) of 1.70° (Fig. 21b). This indicates that the sensor motion within a compacted slab cannot be properly evaluated unless the rigid motion of the external system is first assessed, as it may influence the sensor measurements.

In the direction transverse to compaction, instead, the system that moves the steel mold is very rigid and does not allow rotation. In fact, the X-axis Euler angles recorded by the sensor and, consequently, the X-axis relative rotations are very close to zero (Fig. 21a and b).

It is worth noting that the rigid motion of the roller mold does not depend on the applied load. In fact, the compaction test used to evaluate the roller mold rigid movement involved an increasing load, which did not influence the recorded Euler angles. During the entire test, RR_Y remained constant at 1.70°.

3.4. Roller compactor results

In order to evaluate the actual relative movement between the steel

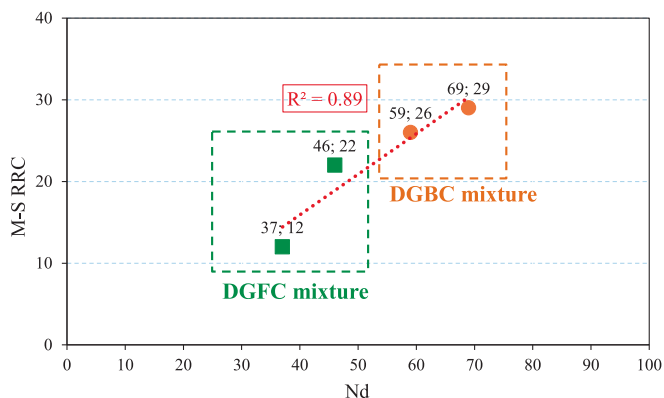


Fig. 20. Novel workability parameter for gyratory compaction M–S RRC vs. N_d .

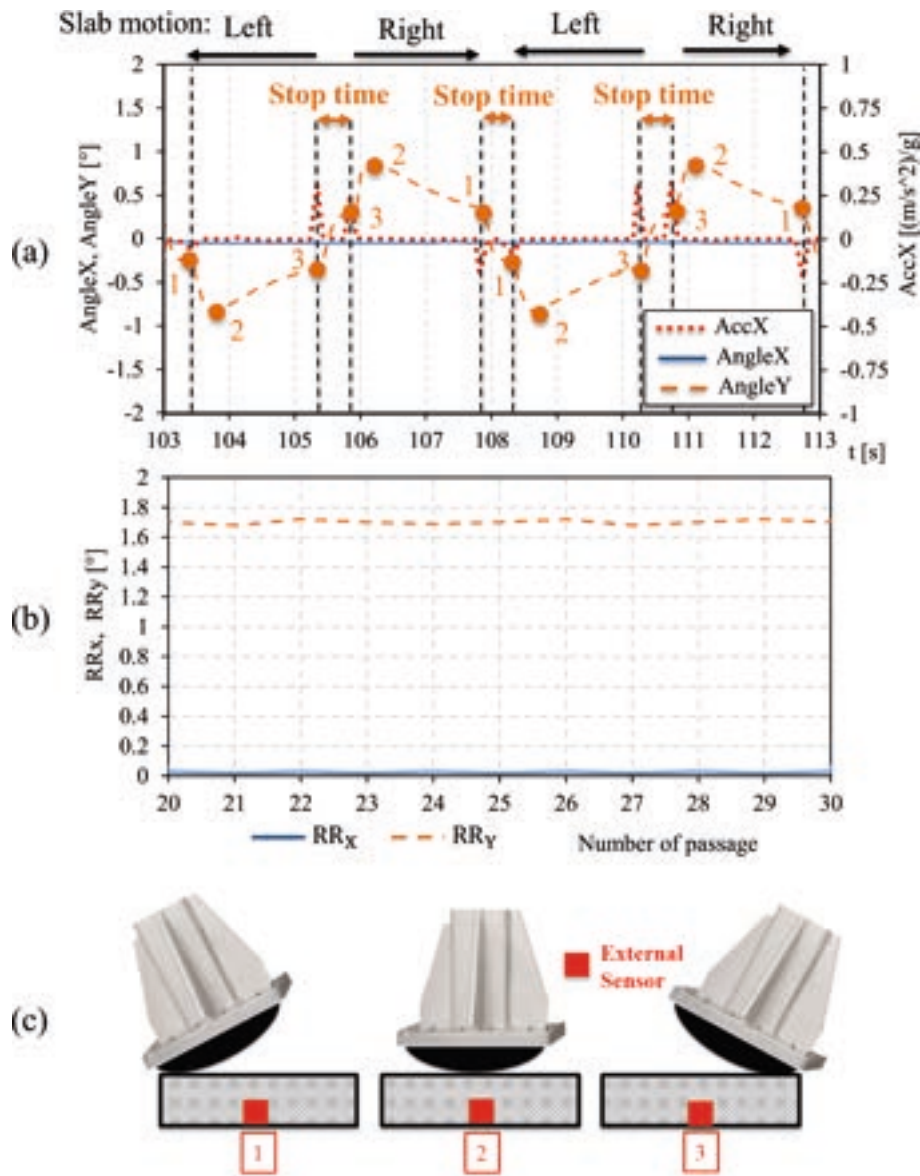


Fig. 21. Roller steel mold motion investigation: (a) Euler angles and x-axis acceleration, (b) relative rotations, (c) motion features.

mold and the sensor during roller compaction, and given the inconsistency of the RRC parameter based on ASTM D8541, the same workability parameter proposed for gyratory compaction (Eq. (2)) was used to evaluate roller compaction tests. It was assumed that RR_i is the relative rotation of the compacted asphalt mixture at i^{th} rolling passage, RR_{i+1} is the relative rotation of the compacted asphalt mixture at $(i + 1)^{th}$ rolling passage, RR_{mold} is the relative rotation related to the rigid motion of the steel mold (1.70° for the y direction and 0° for the x direction, see Fig. 21b), l refers to the length of the x-axis unit (one rolling passage), N_i and N_d are the same as those defined in Section 2.4. By examining the experimental results (Fig. 22), it was observed that the mixture requires five rolling passages to stabilize. During these initial five cycles, the mixture undergoes an early initial compaction phase, which is thus excluded from the determination of the M–S RRC parameter. Therefore, N_i was assumed equal to 5, whereas N_d corresponds to the total number of passages until the target height of 100 mm is reached.

Fig. 22 illustrates, for each test combination, an example of the calculation of the proposed workability parameter M–S RRC. Specifically, the area corresponding to the M–S RRC_Y parameter was

determined by subtracting the relative rotation associated with the mold rigid movement ($RR_{Ymold} = 1.70^\circ$), whereas the area related to the x-axis (M–S RRC_X) was taken as it is, because RR_X related to the mold rigid movement is assumed equal to zero (Fig. 21b). In general, the values of the parameters calculated in the two directions (M–S RRC_X and M–S RRC_Y) are different given the dominance of motion in the compaction direction (which implies rotations around the y axis).

It can be noted that the curves related to relative rotations of the roller compactor (Fig. 22) are quite similar to the one describing the applied load (Fig. 8). As the load increases, the relative rotations (RR_X , RR_Y) also increase.

Fig. 23 shows the M–S RRC values related to the three asphalt mixtures investigated and the two sensor shell geometries. The novel workability parameter appears to be sensitive to the type of mixture, even though a direct comparison between the mixtures cannot be made due to their different target air void contents. In all cases, the values of M–S RRC are higher in the y-direction (M–S RRC_Y), but non-negligible transverse effects were also recorded (M–S RRC_X).

As shown in previous studies for the gyratory compactor [17,18], the results confirm that, even under the action of the roller compactor, the spherical sensor exhibits greater movement than the cubic one, with

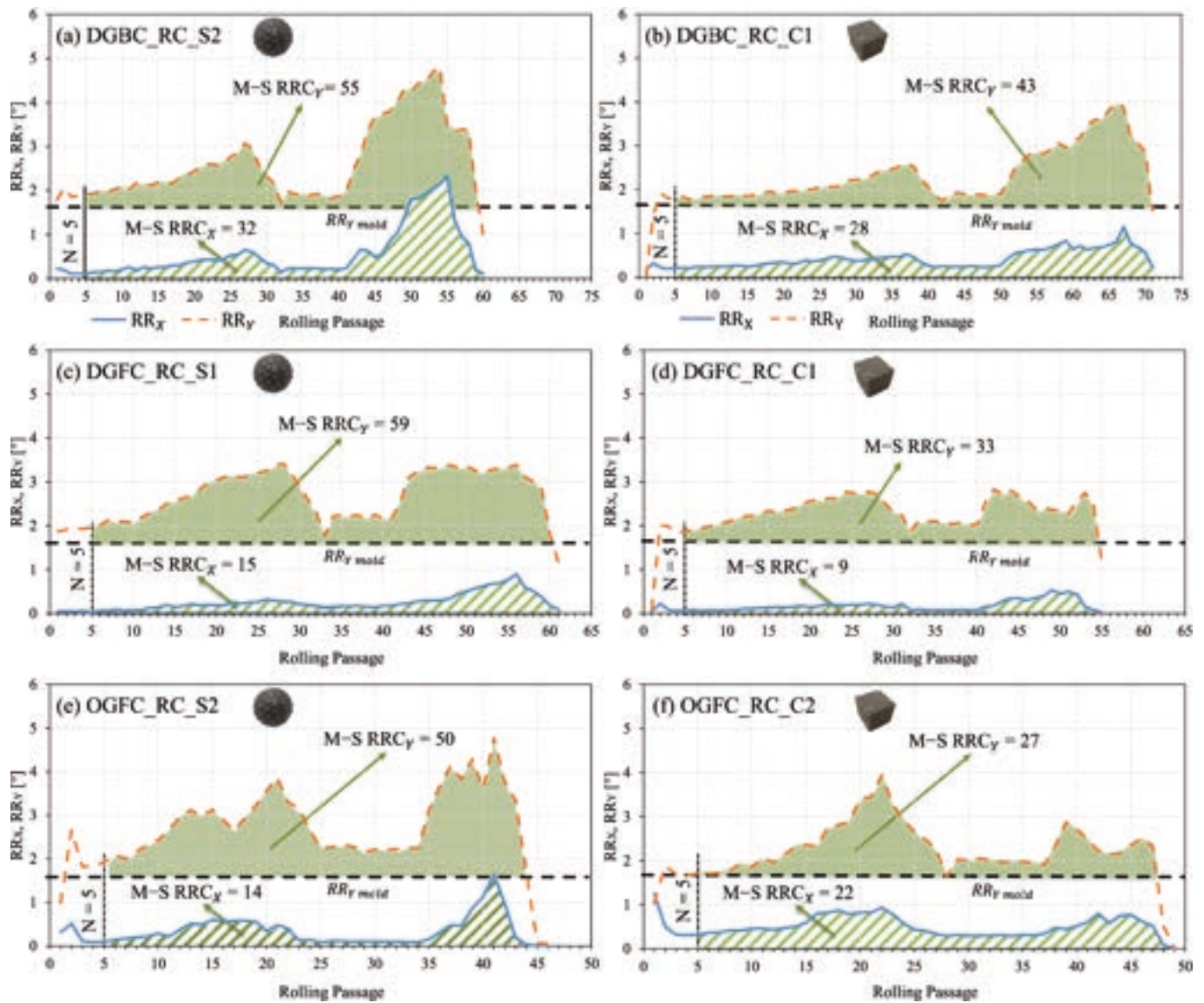


Fig. 22. M–S RRC calculation for three asphalt mixtures and two shell geometries: (a) DGBC mixture and spherical shell; (b) DGBC mixture and cubic shell; (c) DGFC mixture and spherical shell; (d) DGFC mixture and cubic shell; (e) OGFC mixture and spherical shell; (f) OGFC mixture and cubic shell.

differences that can reach up to twice the magnitude. In fact, in the tests performed with the cubic sensor, the rotations measured in the y-direction (caused by the translation of the mold during compaction) were comparable to those in the x-direction, although the latter resulted solely from minor material settlements rather than directly from the actual compaction motion. Because spherical shells exhibit higher sensitivity than cubic ones, the spherical sensor is expected to more effectively detect small variations in mixture workability, even in the case of roller compaction.

4. Conclusions

This study investigated the use of particle-size sensors to analyze laboratory gyratory and roller compaction of asphalt mixtures. The work first evaluated the reliability of ASTM D8541 workability parameters across different gyratory compactors and then addressed the methodological gap in roller compaction by presenting the first application of a steel roller compactor equipped with such sensors. To achieve these objectives, two gyratory compactors, one roller compactor, three asphalt mixtures, an unbound granular material, and two sensor geometries were examined to characterize aggregate motion under both

compaction methods.

The main study findings can be summarized as follows:

- The workability parameters defined in ASTM D8541 are influenced by the rigid movement of the mold, which varies between gyratory compactors; as a result, these parameters may yield different outcomes across machines, highlighting the need for compactor-specific calibration.
- A novel workability parameter (M–S RRC) was proposed, which captures the relative motion between sensor and mold, providing useful information on the actual compaction undergone by the material and showing sensitivity to key factors affecting the compaction process (e.g., gradation curve and NMAS of the asphalt mixture, sensor geometry).
- In gyratory compaction, the novel parameter M–S RRC shows a direct correlation with N_d . Mixtures that reach the target compaction stage at lower N_d values also exhibit lower M–S RRC values, reflecting higher workability.
- Under roller compaction, the spherical sensor moves more than the cubic sensor, exhibiting M–S RRC values that can be up to twice those obtained with the cubic sensor. This behaviour supports its

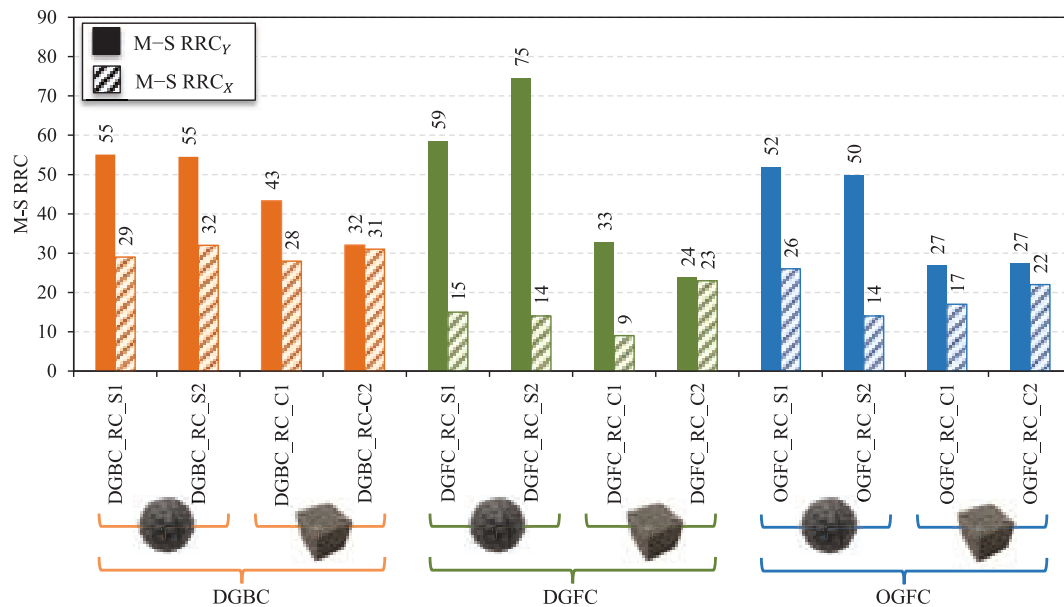


Fig. 23. Mold-sensor relative rotation capacity for three asphalt mixtures and two shell geometries (Roller compactor).

preferential use for detecting subtle variations in mixture workability and compaction variables.

Overall, the M-S RRC parameter shows encouraging potential for describing aspects of compaction behaviour in both gyratory and roller compaction. In gyratory compaction, it exhibits a favorable indicative trend with the Compaction Energy Index (CEI). Under roller compaction, the area associated with the novel parameter may reflect trends qualitatively similar to those observed in the applied load history, although this aspect remains preliminary and requires further investigation.

The proposed M-S RRC parameter yielded promising results in this first application. Nevertheless, further investigations are required to validate this novel workability parameter. Regarding roller compaction, an extended experimental program is already planned, including tests performed under energy-controlled conditions to directly compare the workability of different asphalt mixtures for the same compaction energy. Future work will also aim at the final upscaling of the use of the developed particle-size sensors from laboratory roller compaction to field compaction.

CRediT authorship contribution statement

Omar Guazzaroni: Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **Lorenzo Paolo Ingrassia:** Writing – original draft, Methodology, Formal analysis, Conceptualization. **Amedeo Virgili:** Software, Methodology, Formal analysis. **Andrea Graziani:** Writing – original draft, Methodology, Formal analysis, Conceptualization. **Francesco Canestrari:** Writing – review & editing, Methodology, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

None.

Data availability

Data will be made available on request.

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