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Sound Insulation Performance of Prefabricated Concrete Partitions in Hellenic School Buildings

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Abstract: The scope of this study is to investigate flanking noise transmission through joints between prefabricated concrete elements in Hellenic school buildings; such joints apparently are non-existent in the wholesome structure of ordinary concrete buildings. Sound insulation measurements were carried out in two prefabricated concrete buildings of the *cell* type; the latter involves demountable/reusable concrete elements (the *cells*); in this case, apparently, flanking noise transmission at joints, may be even more pronounced. A sample of seventeen façade and interior partitions of classrooms was tested. Sound insulation was also predicted based on classical theory. Analysis of the measured data confirms, by and large, the satisfactory sound insulation performance of the test partitions, with the exception of composite partitions which involve door and window openings. The latter were identified to be a major source of sound insulation deterioration. The importance of meticulous sealing of joints is demonstrated.

Key words: Airborne noise transmission, flanking paths, prefabricated concrete buildings, classrooms.

1. Introduction

Freedom from noise is a significant design parameter for the environmentally friendly educational workplace, and determines considerably construction detailing. Indeed, in school classrooms it is essential to reach adequate ratings of sound insulation for dividing walls, and control flanking transmission paths.

With the introduction of prefabricated concrete buildings in modern world (Section 1.1 below) a trend for school buildings of this kind is established [1-5]. Nevertheless, unlike ordinary concrete buildings which are made up of wholesome (monolithic) structure, prefabricated buildings are set up of jointed building elements (Figs. 1 and 2). This can be a limiting factor for the sound insulation ratings achieved, since joints are potential paths of flanking noise transmission (Fig. 3). This limitation apparently, may be even more pronounced with joints of demountable/reusable prefabricated building elements. A type of school buildings which employ such joints has been developed by the Hellenic Organization of School Buildings [5] since the beginning of the new millennium. The aim of the present study is to investigate the sound insulation performance of concrete partitions in Hellenic school buildings of the said type; this study involves acoustic measurements in situ.

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1.1 Prefabricated Concrete Buildings

The notion of prefabricated buildings dates back to antiquity [6]. Nevertheless, modern building prefabrication evolved rapidly only after World War II. Relative advantages are described in Ref. [7].

The Hellenic Organization of School Buildings (ΟΣΚ) also has played an important role in the industry of prefabricated concrete buildings [5]. Indeed, ΟΣΚ has developed amongst others, the system of prefabricated concrete *cells*; this involves concrete boxes, namely the *cells* (Fig. 1), which can easily be combined with each other in situ to form classrooms (Fig. 2, and Section 4 below) thus saving considerable construction time. This system soon was

Fig. 1 Prefabricated concrete *cell* [5].

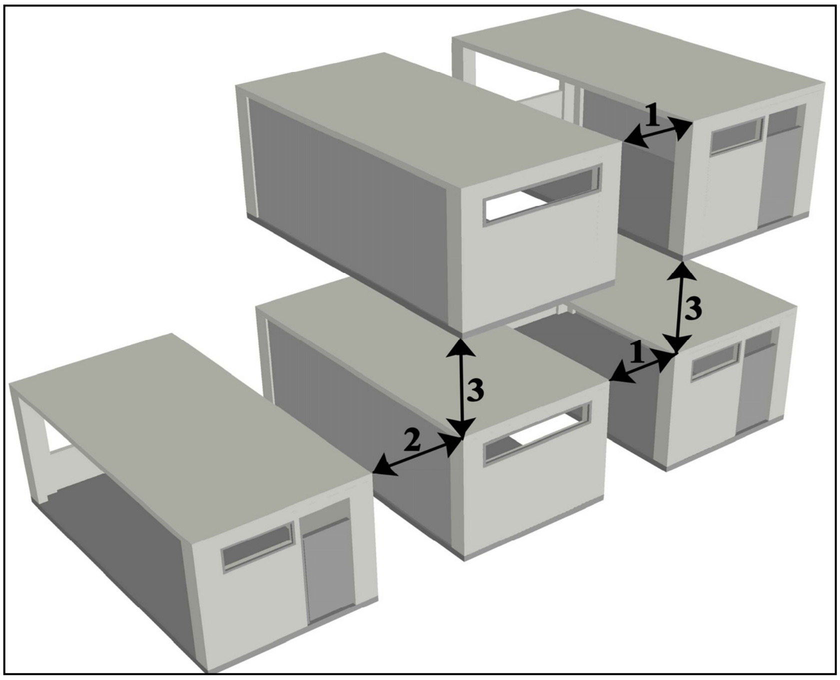

Fig. 2 Prefabricated cell combinations. "1": "wrap around" joint within classroom; "2": joint between adjacent classrooms; "3": joint between superimposed classrooms.

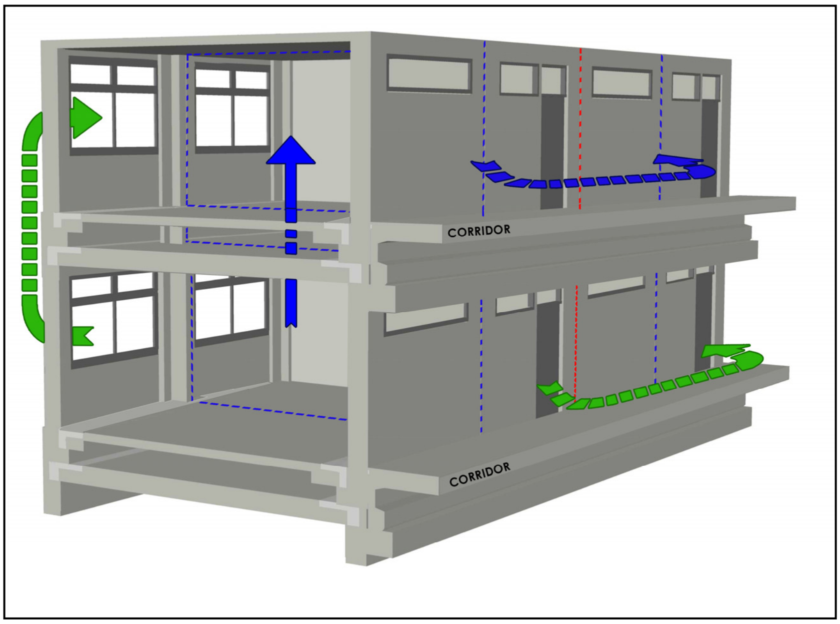

Fig. 3 Flanking transmission paths.
---: "wrap around" joint within classroom (Fig. 6).
---: joint between classrooms (dividing partition) (Fig. 7).
●: doors or window openings.

extended to produce two storey school buildings [3], with possibility for demounting and reusing the units at distinct locations whenever this is called for; for instance with fast changing densities of population, after earthquakes, etc. [5]. The *cell* type concrete prefabrication has been extensively applied in Hellenic schools, and currently efforts are directed towards improving this environmentally. Within this context, checking the acoustical performance of this system is also worth trying.

1.2 Review of Past Work

The importance of proper acoustic environment in school classrooms has been acknowledged by researchers over the past few decades [8-13]. Nevertheless, only scanty efforts have been made to investigate the acoustics of prefabricated concrete buildings [7, 14]. The present paper is a revision and extension to Ref. [7].

2. Experimental Design and Procedure

Measurements of airborne sound insulation of concrete partitions were carried out in two school buildings; the latter are located in relatively quiet suburbs of Athens, namely in Gerakas and Peristeri, and they date back to years 2010 and 2003 respectively. The selected buildings are, in principle, of identical design, they are typical of the *cell* type prefabricated concrete school (Fig. 1), and accommodate 300 pupils each, in two storeys. In each floor, *cells* are placed side by side; *cells* are also superimposed (Fig. 2).

Four types of dividing partitions were tested, namely **A, B, C** and **D** respectively (Table 1, Figs. 4 and 5) and will be presented below in association with inter *cell* joints. Joints between *cells* occur in three types. The first type is a joint that wraps around the *cell* by way of a ribbon (Fig. 2, case 1); this joint is 1.0 cm wide and it is sealed with polyurethane foam so as to be air-and-water tight. A resilient airtight seal is employed at the finish (Figs. 5-7). This joint runs across first the partition between classroom and corridor (test partition **type B**), secondly, the slab between superimposed classrooms (test partition **type C**) and thirdly, the external wall classroom (test partition **type D**).

Another type of joint occurs at the interface between

Table 1 Types of test partitions, and samples.

Test Partitions			
Type		Description	Sample
A	A_G	Cavity partition between classrooms in school of Gerakas (see Fig. 6)	A_{Gi}, A_{Gii}, A_{Giii} SW: 350 (Fig. 4)
	A_P	Cavity partition between classrooms in school of Peristeri (see Fig. 6)	A_{Pi}, A_{Pii}, A_{Piii}, A_{Piv} SW: 350 (Fig. 4)
B	B_G	Composite partition between classroom and corridor in school of Gerakas (see Fig. 8)	B_{Gi}, B_{Gii} SW: 350 (Fig. 4)
	B_P	Composite partition between classroom and corridor in school of Peristeri (see Fig. 8)	B_{Pi}, B_{Pii} SW: 350 (Fig. 4)
C	C_G	Cavity floor slab in school of Gerakas (see Fig. 9)	C_{GI}, C_{GII} SW: 400 (Fig. 5)
	C_P	Cavity floor slab in school of Peristeri (see Fig. 9)	C_{PI}, C_{PII} SW: 400 (Fig. 5)
D	D_P	Façade composite partition in school of Peristeri (see Fig. 10)	D_{Pi}, D_{Pii} SW: 350 (Fig. 4)

SW: Surface weight of reinforced concrete only (kg/m^2).

classrooms (Fig. 2, case 2) and forms test partition **type A**; the latter is a cavity partition and involves two layers of 7.0 cm thick concrete on either side of a 6.0 cm air gap; in one of the test schools, namely in Peristeri, this cavity is partly filled with two polystyrene panels 2.5 cm thick each, so that in the end a 1.0 cm air gap is left between adjacent *cells* (Fig. 8). Polystyrene infill was initially used for thermal insulation; however, soon this technique was abandoned, owing to limitations during transportation of this brittle insulator attached to the *cells*.

The last type of joint between *cells* occurs at the interface between superimposed classrooms (Fig. 2, case 3). This forms test partition **type C**. The latter is a cavity concrete slab that involves a 15.0 cm wide air gap. The top layer (floor) is a 5.0 cm thick beam slab with an array of beams 11.0 cm deep; inter beam space is 70.0 cm and it is filled with 11.0 cm thick polystyrene panels. Each beam is 7.0 cm wide. The bottom layer (ceiling) is a sandwich slab that involves two leaves of 5.0 cm thick concrete each, with a 6.0 cm polystyrene core (Fig. 9). Impact sound insulation of the test slabs is not investigated, since this type of insulation is independent of flanking airborne noise transmission through test joints. At predetermined locations around the perimeter of cavity partitions, metal ties are used, in order to fix *cells* with each other. This is considered also, to limit sound bridges.

Amongst test partitions, **types B** and **D** refer to composite partitions (Table 1, Figs. 9 and 10) which involve door and window openings as well as a solid part. The latter is a sandwich construction of two layers of 7.0 cm thick concrete with a 6.0 cm polystyrene core; obviously, the maximum insulation that can be achieved in this case is virtually determined by the mass. Furthermore, partition **type B** involves also a door and a clerestory window. A large glazing of like construction is also involved in the façade partition (**type D**) (Fig. 3, Table 1). The surface ratio of solid-part to aperture is 0.75 and 0.51 for partitions **type B** and **D** respectively.

Field measurements were carried out in 1/3 octave bands from 100 Hz to 3,150 Hz, according to ISO standard 140/4-1978 part 4 and ISO standard 16283-3:2016 part 3 for inside and external wall partitions respectively. All measurements were

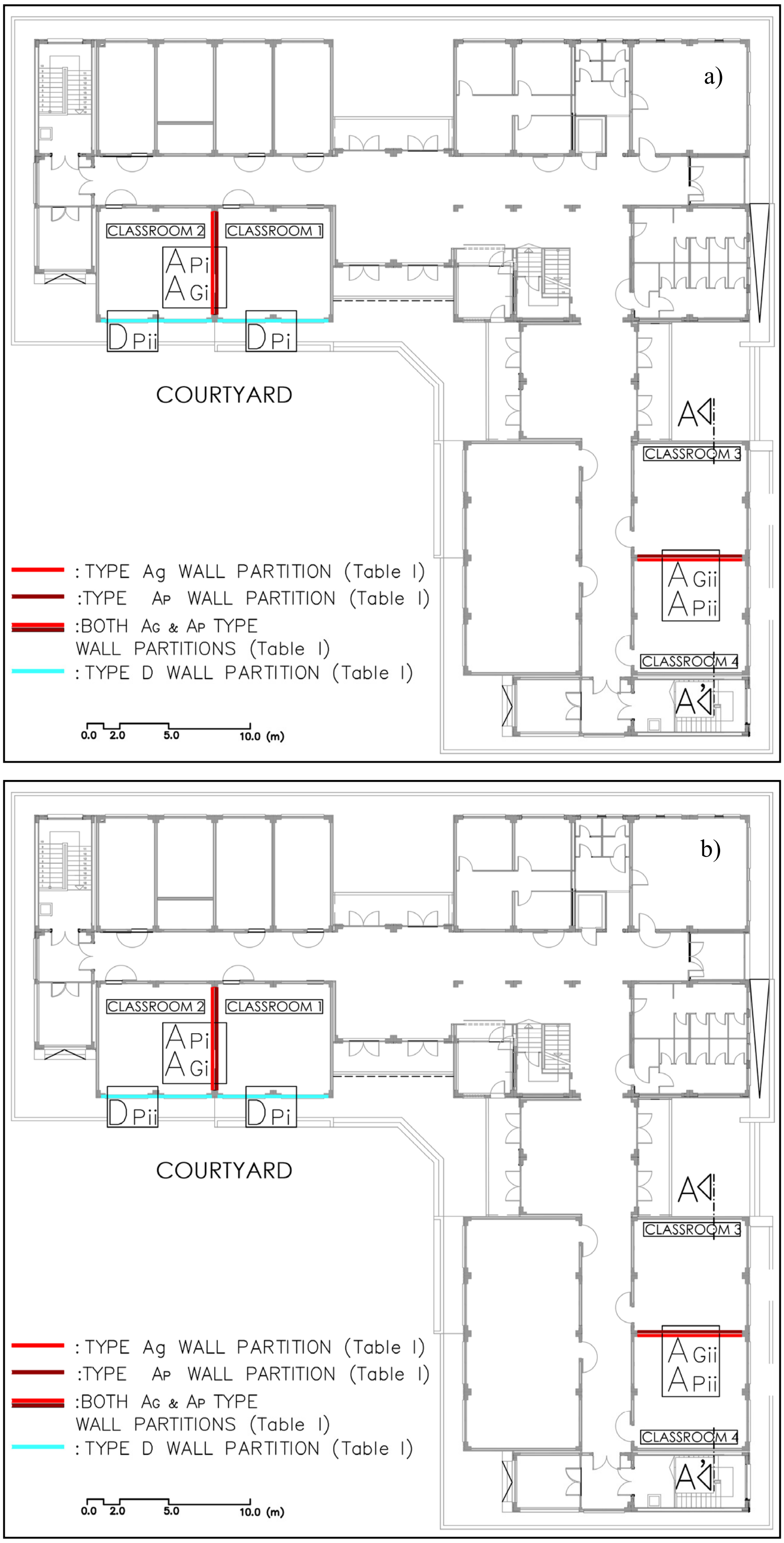

Fig. 4 School plans indicating test partitions: (a) ground floor (A_I, A_{II}) and (b) first floor (A_{III}, A_{IV}, B_I, B_{II}).

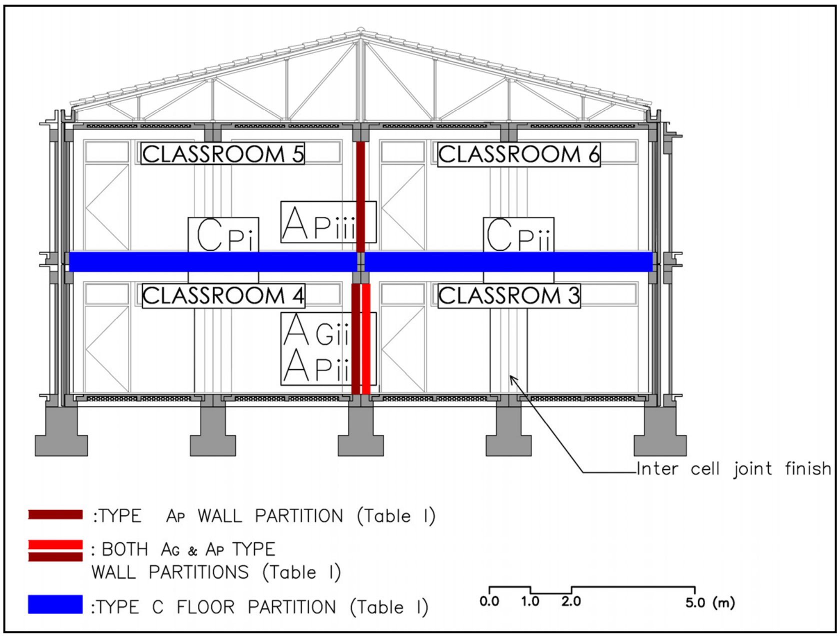

Fig. 5 Section A-A' indicating test partitions *(*C_I, C_{II}*)*.

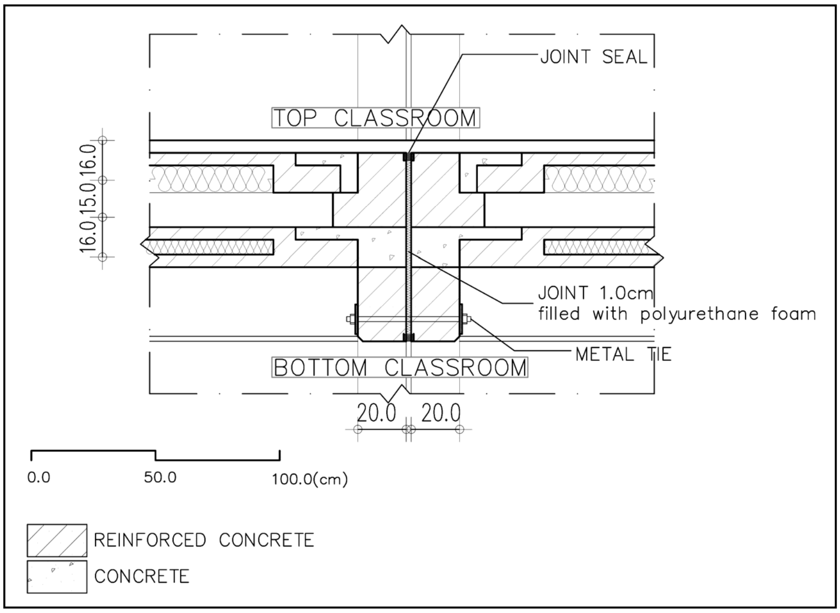

Fig. 6 Drawing detail at the joint between prefabricated *cells* ("wrap around" joint within classroom).

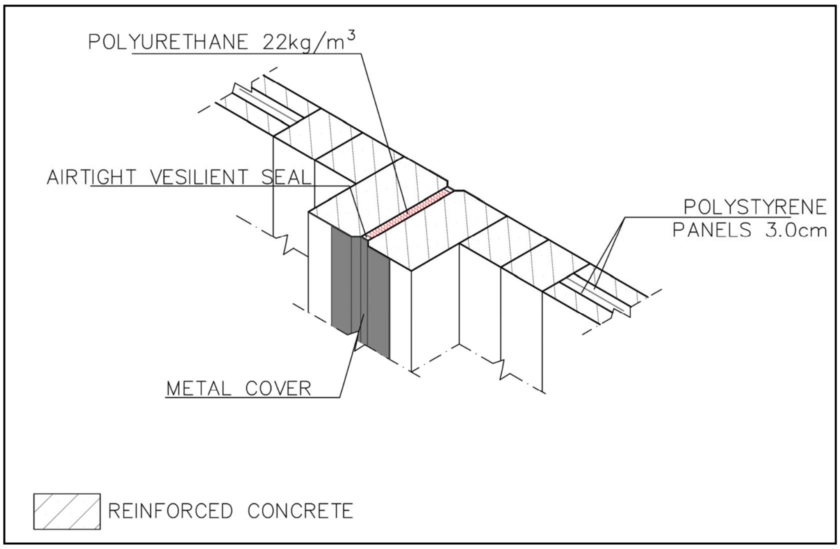

Fig. 7 Drawing detail of joint between prefabricated *cells* (see Fig. 6).

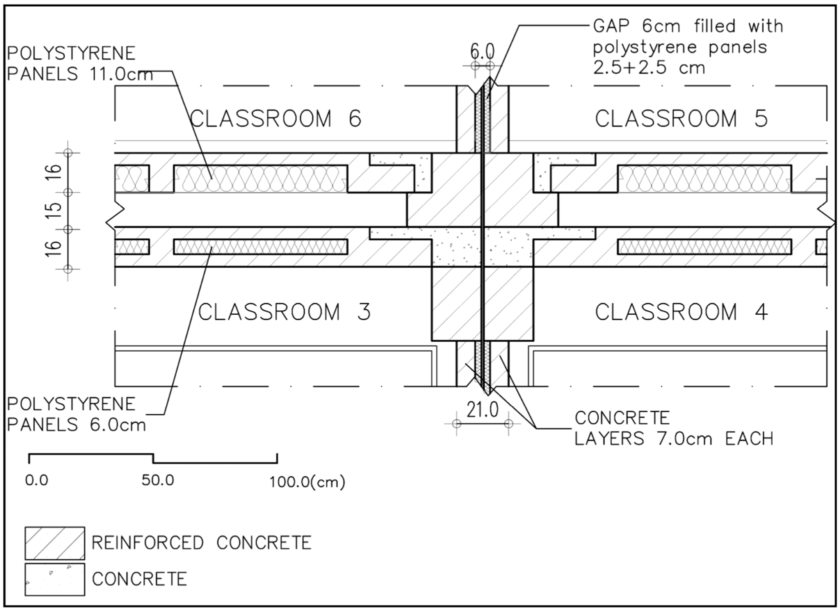

Fig. 8 Drawing detail at the joint between adjacent classrooms (partition type A), and at the joint between superimposed classrooms (slab/partition type C).

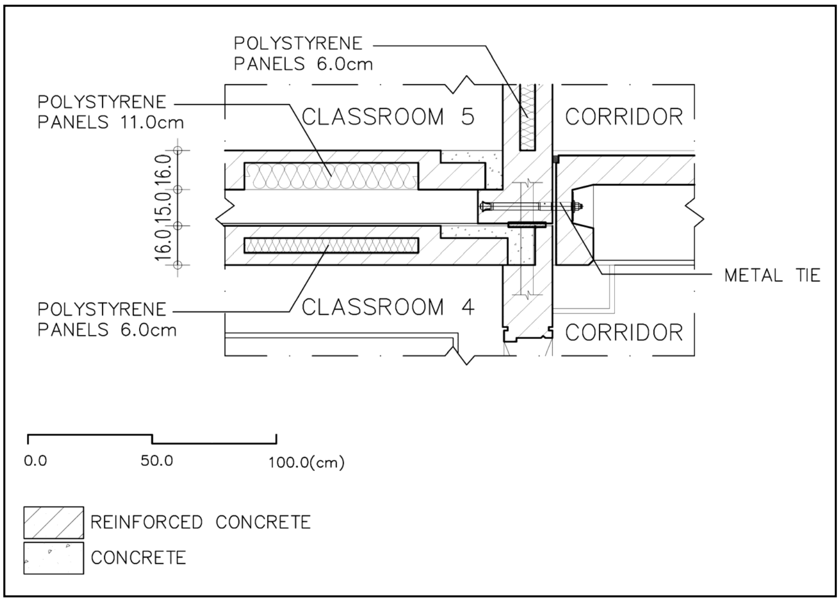

Fig. 9 Drawing detail of concrete slab (partition type C) at the junction with corridor.

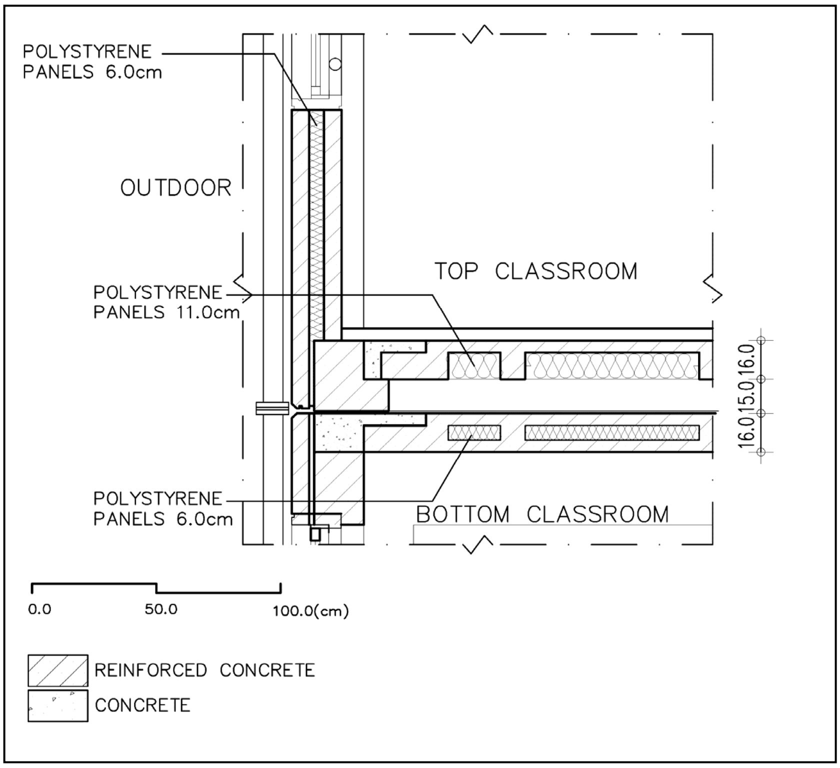

Fig. 10 Drawing detail at the façade partition (type D).

performed in unoccupied classrooms. Acoustic equipment involved a sound level meter "Hand-held Analyzer Type 2270", a microphone "4189", a loudspeaker "Omni Power 4296" and a sound amplifier "Lab gruppen 2716" (all by Brüel & Kjær). Typical measuring layout is shown in Fig. 11.

3. Analysis of Experimental Data

Prediction of sound insulation performance of the test partitions was used for comparisons with measured data. Computations were based on classical theory [15] derived formulae. In particular, for partition

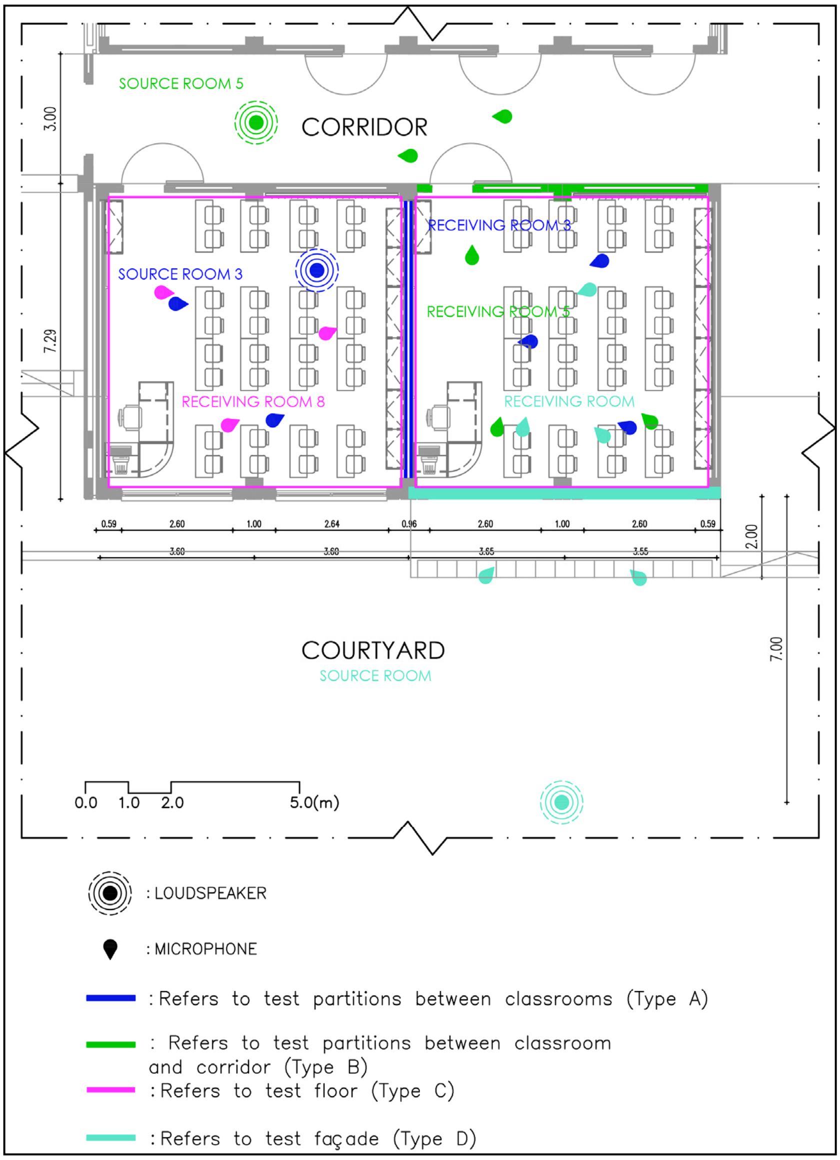

Fig. 11 Typical measuring lay out.

type A and **C**, the empirical formula [16, 17] was employed:

$$R = 20\log(md) + 34 \quad (1)$$

R: mean frequency sound reduction index over 1/3 oct. bands from 100 to 3,150 Hz (dB), m: combined surface weight (kg/m^2), d: cavity depth (m).

This formula refers to the mass controlled response of the cavity partition, and assumes that sound bridges are limited to a minimum. In present case this assumption is expected to be realistic (Section 2 above). It is also assumed that there is absorbent infill between the two layers to stop cavity resonances, which admittedly is violated in present case (Section 2 above); therefore, a lower than theoretical performance is anticipated in the field tests. The theoretical spectral distribution of the predicted R was then determined according to Ref. [18] (Figs. 13 and 14). The lowest cavity resonance (f_{low}) was worked out according to:

$$f_{low} = 170/d \quad (2)$$

d: cavity depth (m).

Nevertheless, the slope of 12 dB/oct. (Figs. 13 and 14) may be degraded by coincidence effect, higher resonance frequencies, etc., therefore, Schild et al. [18]

reasonally admit that prediction can only be of a qualitative nature. Furthermore, when cavity depth becomes 1.0 cm (Section 2 above) the maximum insulation which can be achieved in the important frequency range (in present case, for frequencies below, at least, 2,700 Hz ($f \leq 27/d$, d: cavity depth (m)) is determined by the mass response [15]; this insulation of course, is further degraded in practise, by coinsidence, resonance, etc. effects.

$$R = 20\log(mf) - 48 \quad (3)$$

R: sound reduction index (dB), m: mass (kg/m^2), f: frequency (Hz).

For the remaining partition types, namely **B** and **D**, the following typical equation for composite partitions was used in the predictions.

$$Rc = 10\log(1/T_{av}) \quad (4)$$

Rc: sound reduction index of composite wall (dB), T_{av}: sound reduction coefficient of composite wall (see Eq. (5)), T_1, T_2, etc.: sound reduction coefficient respectively of the elements 1, 2, etc., S_1, S_2, etc.: surface area respectively of the elements 1, 2, etc. (m^2).

$$T_{av} = (T_1 S_1 + T_2 S_2 + \cdots)/(S_1 + S_2 + \cdots) \quad (5)$$

$$R = 10\log(1/T),\ \text{dB} \quad (6)$$

For notation see Eqs. (3) and (4) above.

For the test composite partitions the sound reduction index of the solid part (element 1) (Section 2 above) was predicted according to mass law theory (Eq. (3)). Data for the sound insulation performance of the doors and windows involved (elements 2 and 3) are shown in Table 2.

Theoretical predictions of course assume also no flanking transmission; therefore, it can be anticipated that measured insulation in present test buildings (Section 2 above), will be inferior to predictions.

For each partition type tested, the adequacy of the measured sound insulation was also evaluated. A strict noise criterion NR30 was adopted [19] for present classrooms in quiet suburbs. In particular, the requisite insulation between classrooms (partition **type A**, and **C**) was evaluated with regard to teacher's raised voice level penetrating in the receiving classroom. The requisite insulation between classroom and corridor (partition **type B**), was evaluated with regard to noise from pupils in the school corridor penetrating in the receiving classroom. Last the requisite insulation for the test façade (partition **type D**) was evaluated with regard to, on the one hand noise from pupils in school courtyard, and on the other hand moderate urban traffic noise (Table 3).

4. Results

Results from measurements and theoretical predictions are shown in Table 4 and Figs. 12-14. Results from evaluations of partitions are shown in Figs. 15-18.

5. Discussion

For partitions **type A** (Table 1), significant difference was identified in the mean weighted sound reduction index (R'_w) between the two test schools (Tables 4 and 5). This can be explained with reference to polystyrene panel infill, used with cavity partitions in one of the test schools (Section 2 above). Removal of the said infill in partitions of the other school, has allowed for relatively increased discontinuity between the two partition layers; consequently, sound insulation was upgraded. For all cavity partitions tested (**type A and C**) theoretical response was found to be superior to measured R'_w by 6 to 16 dB (Table 4); however in view of violation of basic assumptions of prediction model (Section 3 above) this comparison may be only of a qualitative nature. Nevertheless, measured sound reduction index (R') was found to satisfy the noise criterion adopted (Figs. 15 and 17). It can be inferred that first, the test cavity walls and slabs are suitable for the targeted insulation, and secondly, flanking airborne noise transmission is relatively insignificant. The importance of meticulous sealing and maintenance of joints between *cells*, is explicit.

Furthermore, for all composite partitions tested (**types B** and **D**), theoretical response was found to be

Table 2 Sound reduction index (*R*) of laboratory measurements for doors and windows [20] used in the test schools.

1/3 oct. band (Hz)	Sound reduction index—*R* (dB)	
	Hollow core door (5 + 35 + 5) mm with normal edge cracks	Openable, double glazing (4 + 12 + 4) mm
100	12.7	21.0
125	14.0	24.0
160	15.7	29.0
200	17.3	22.0
250	19.0	26.0
315	20.3	23.0
400	21.7	29.0
500	23.0	33.0
630	22.0	33.0
800	21.0	34.0
1,000	20.0	35.0
1,250	19.0	35.0
1,600	18.0	36.0
2,000	17.0	37.0
2,500	18.3	36.0
3,150	19.7	34.0

Table 3 Sound pressure level (SPL) respectively, of teacher's raised voice at 1.00 m from source* [21], pupils in school corridor [8], pupils in school courtyard [8], and moderate urban traffic [22].

Oct. bands (Hz)	SPL (dB)			
	Teacher	Pupils in corridor	Pupils in courtyard	Traffic noise
125	67.0	59.0	80.0	59.0
250	64.0	58.6	75.0	58.1
500	72.0	65.0	73.0	60.4
1,000	67.0	60.0	70.0	60.4
2,000	65.0	60.0	67.0	59.9
4,000	61.0	66.5	61.0	57.5

*It is assumed that teacher's voice level equals actor's voice level.

Table 4 Measured weighted sound reduction index (R'_w) of test partitions.

Test partitions		Weighted sound reduction index (dB)		
Type	Samples	R'_w	R'_w mean *st. dev.*	R_w (theoretical prediction)
A	A_{Gi}	48	47.5 ± *0.58*	53.5
	A_{Gii}	47		
	A_{Giii}	48		
	A_{Pi}	45	44.5 ± *1.3*	61.0
	A_{Pii}	43		
	A_{Piii}	44		
	A_{Piv}	46		
B	B_{Gi}	24	24.0 ± *0.0*	31.0
	B_{Gii}	24		
	B_{Pi}	26	25.0 ± *1.4*	
	B_{Pii}	24		
C	C_{Gi}	55	53.0 ± *1.3*	63.0
	C_{Gii}	51		
	C_{Pi}	55	54.5 ± *0.7*	
	C_{Pii}	54		
D	D_{Pi}	33	32.0 ± *1.4*	38.0
	D_{Pii}	31		

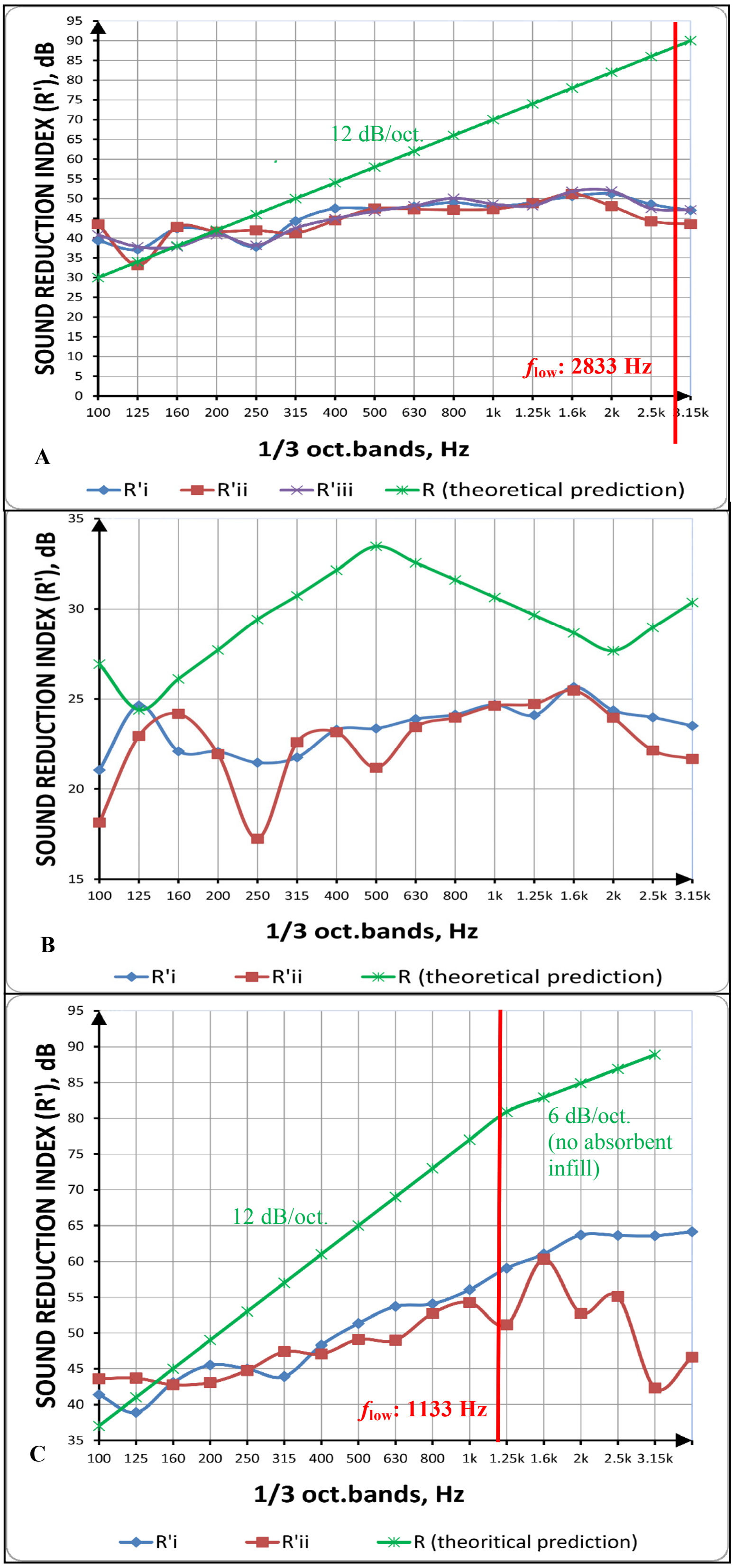

Fig. 12 Measured sound reduction index of partition type A, B and C respectively in school of Gerakas (Table 1). f_{low}: lowest cavity resonance.

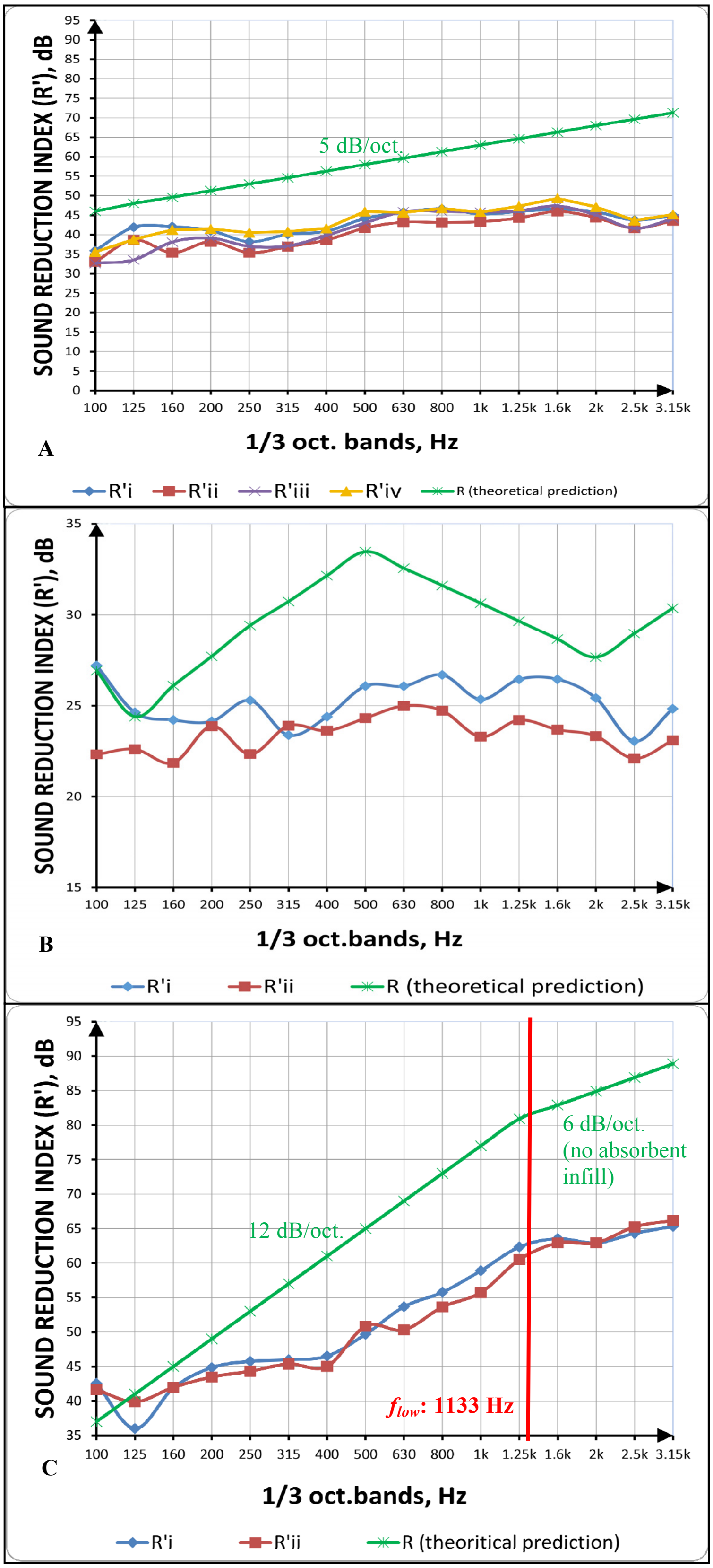

Fig. 13 Measured sound reduction index of partition type A, B and C respectively in school of Peristeri (Table 1). f_{low}**: lowest cavity resonance.**

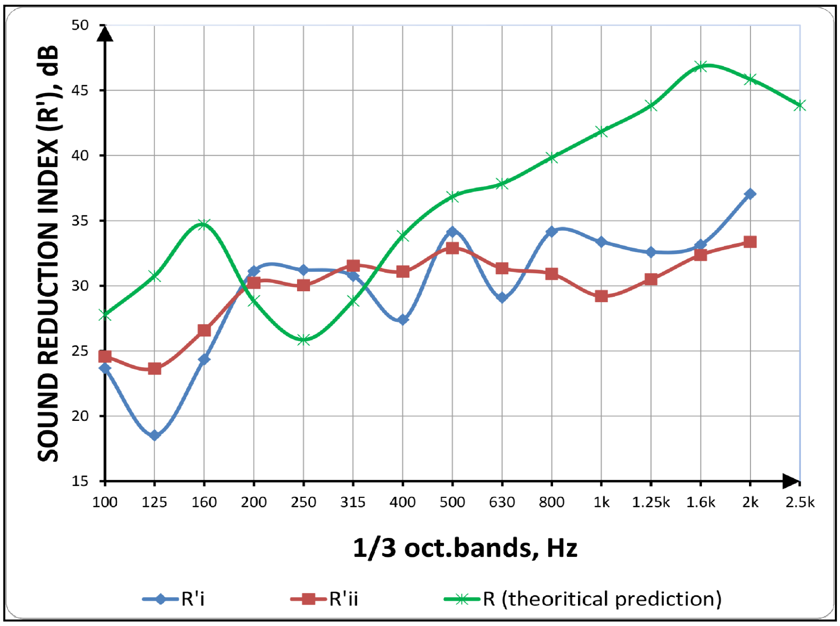

Fig. 14 Measured sound reduction index of partition type D in school of Peristeri (Tables 1 and 2).

Table 5 Comparison of measured weighted sound deduction index of test partitions, between schools/(results of analysis of variance test).

Partition type	F-ratio	Significance
A	15.2	0.01
B	1.0	0.42
C	0.5	0.54

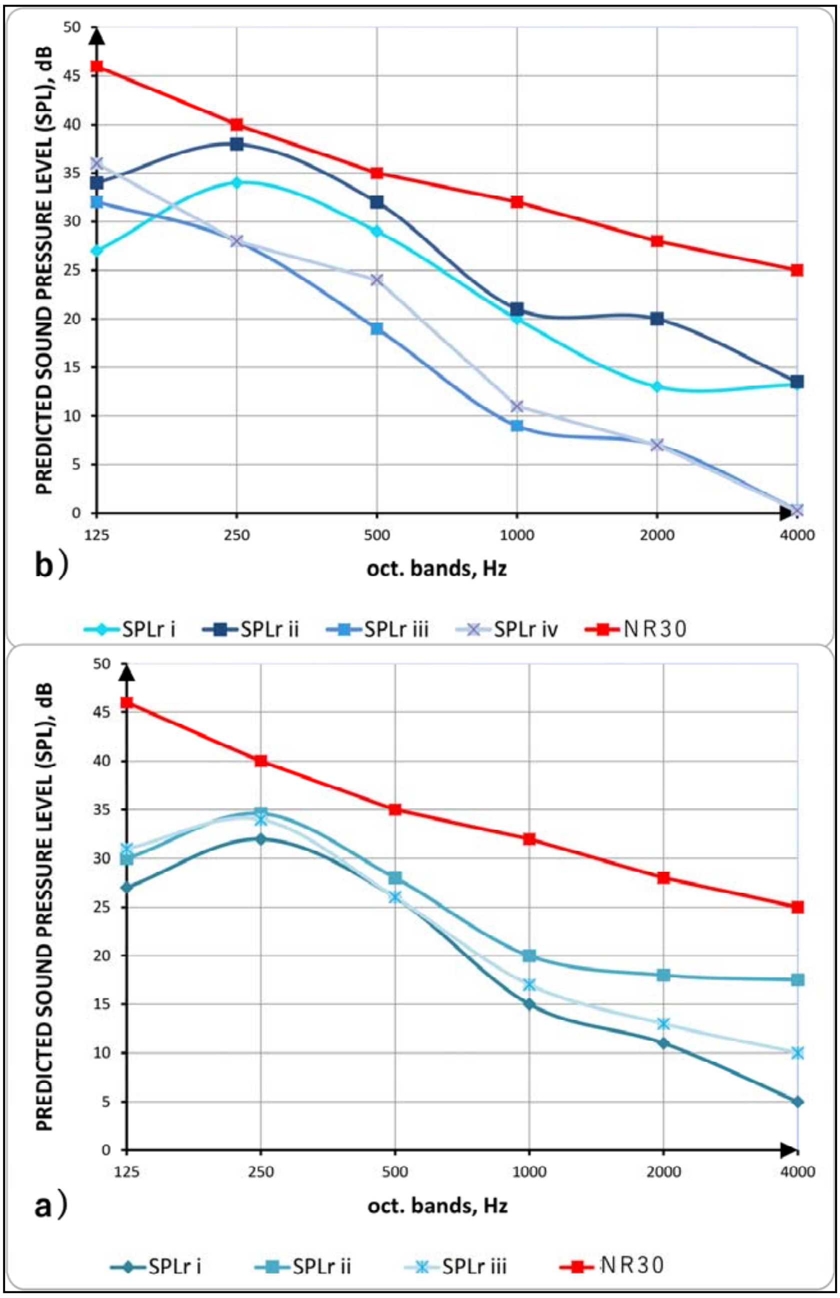

Fig. 15 Evaluation of partition type A. Predicted sound level of teacher's voice penetrating in the receiving classroom (SPLr), respectively in (a) Gerakas, and (b) Peristeri. i, ii, iii, iv refer to test partitions.

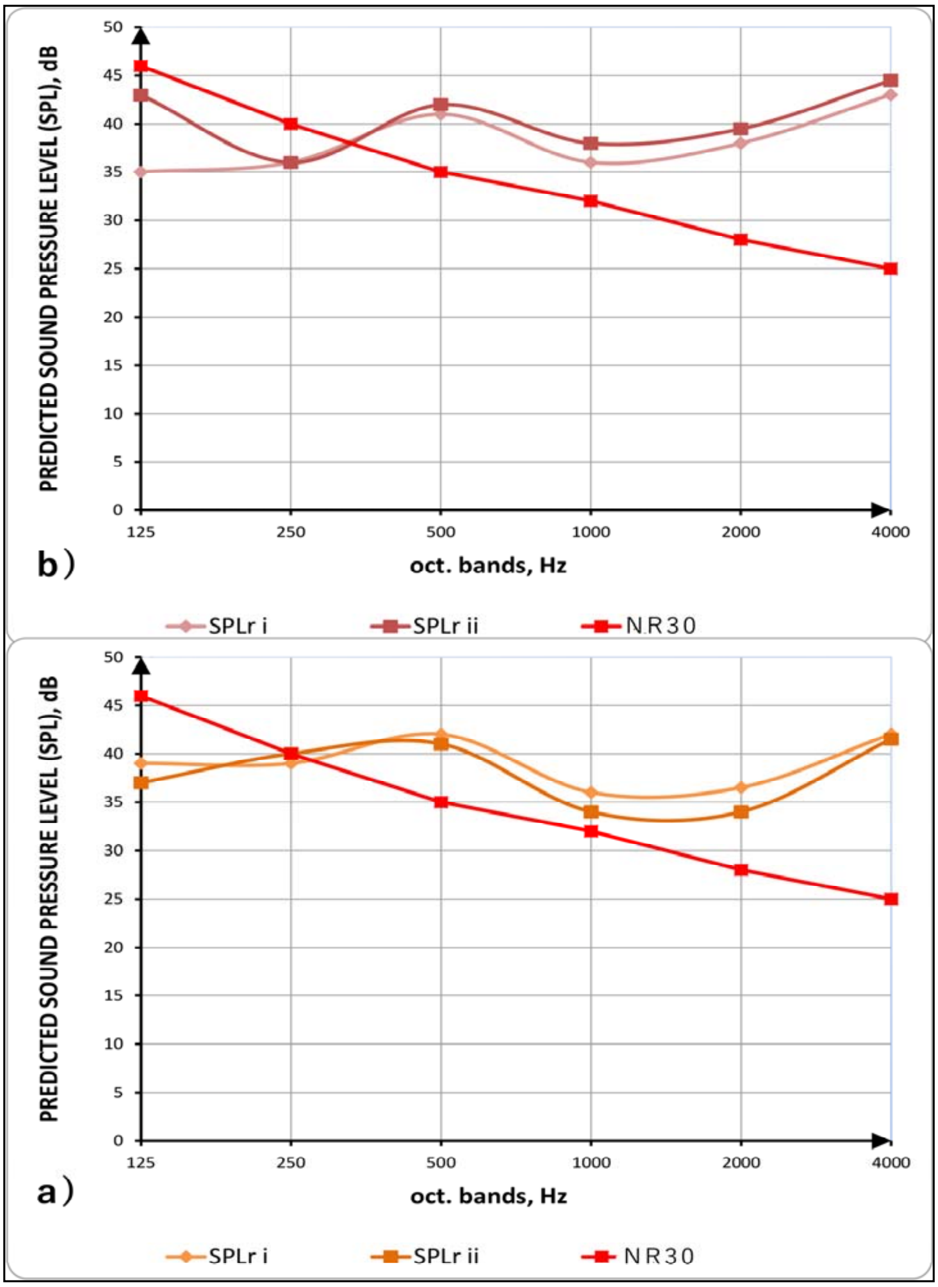

Fig. 16 Evaluation of partition type B. Predicted sound level of pupils in school corridor, penetrating in the receiving classroom (SPLr), respectively in (a) Gerakas, and (b) Peristeri. i, ii refer to test partitions.

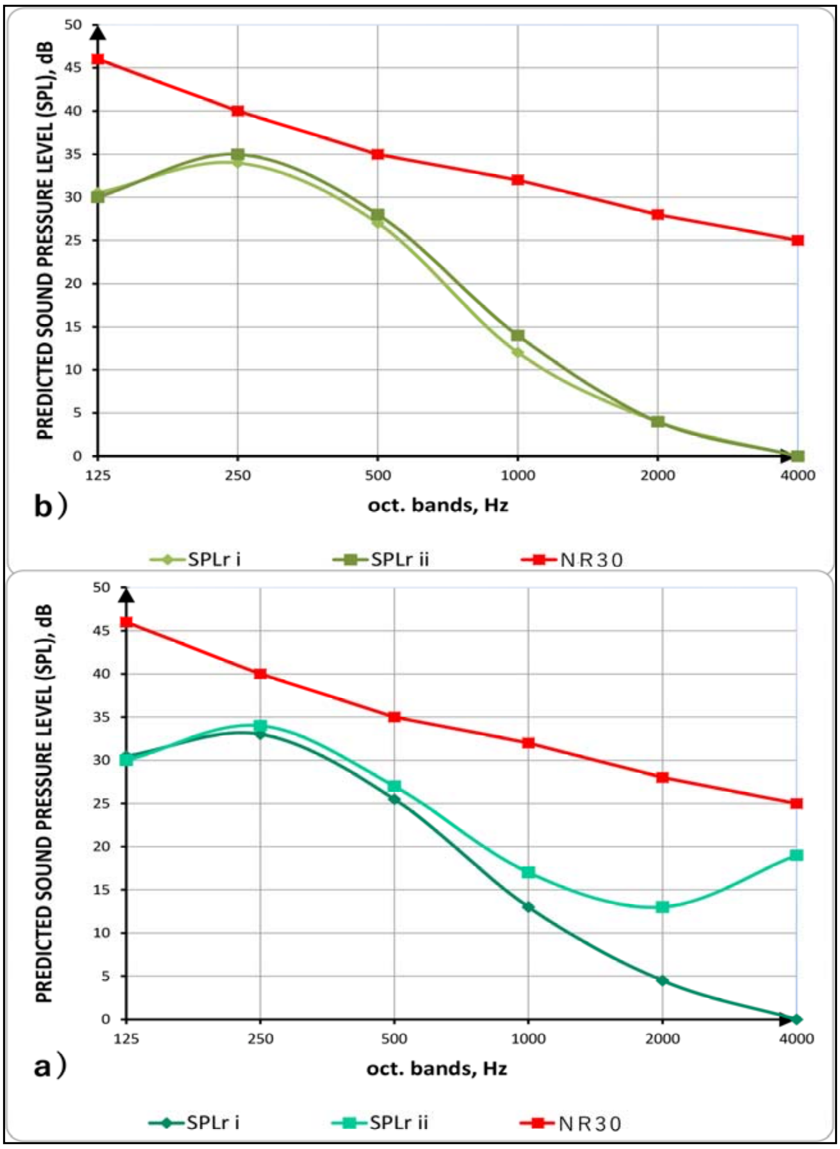

Fig. 17 Evaluation of partition type C. Predicted sound level of teacher's voice penetrating in the receiving classroom (SPLr), respectively in (a) Gerakas, and (b) Peristeri. i, ii, refer to test partitions.

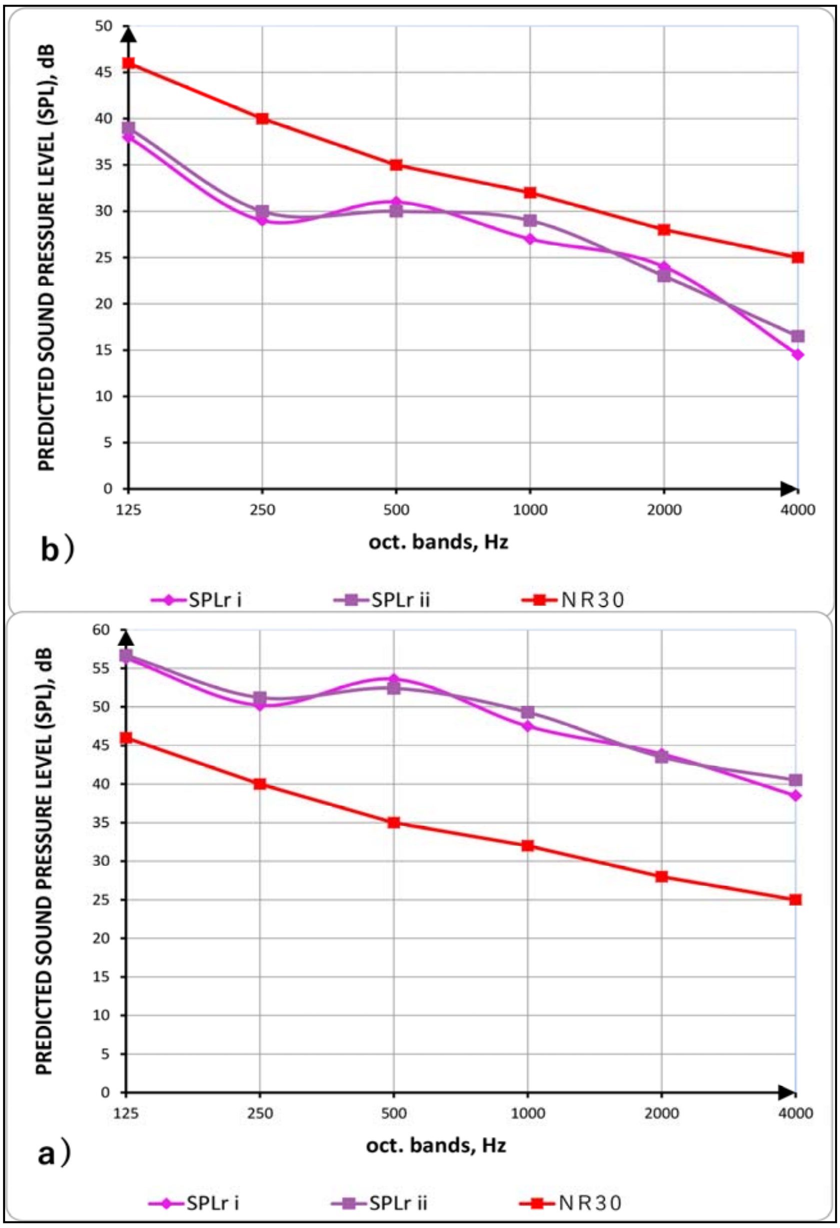

Fig. 18 Evaluation of partition type D (in Peristeri). Predicted sound level penetrating in the receiving classroom (SPLr), respectively of (a) pupils in school courtyard, and (b) moderate urban traffic. i, ii refer to test partitions.

superior to measured R'_w by 6 dB (Table 4). However, for typical school noise sources (Table 3), neither theoretical nor measured insulation was found to satisfy the adopted noise criterion (Figs. 16 and 18). The inter *cell* ("wrap around") joint across test partitions, might have played a negative role in this. However, by inspection to the relatively poor sound insulation specifications of the door and windows involved (Table 2), it is obvious that these elements are a major source of the poor insulation measured. Nevertheless, the test façades (partition **type D**) were found suitable to face moderately noisy urban streets (Fig. 18, case b).

For each partition type tested, repeatability of results between partitions confirms reliability of present measurements (Figs. 12-14, Table 4).

Although this study is based on measurements in the unoccupied classrooms, it is most likely that full classroom conditions would not affect in a significant way present findings.

6. Conclusions

Comparisons between measurements and predictions of sound insulation for the test prefabricated partitions, demonstrated the limitations inherent in the classical prediction model and made explicit the need for full scale measurements. Conclusions from the present acoustic measurements are shown below.

For the test cavity walls and slabs, it was demonstrated that first, these are suitable for the targeted insulation, and secondly, flanking airborne noise transmission is relatively insignificant; this implies that the relevant joint between prefabricated *cells*, contributes positively to the overall sound proof performance; meticulous sealing and maintenance at inter *cell* joints becomes explicit.

It was also demonstrated that the test composite walls, such as in classroom façade and between classroom and corridor, are not suitable for the targeted insulation, owing mainly to poor insulation of doors and windows involved. It is inferred that, non-synchronization between distinct classes with respect to school break, could seriously degrade freedom-from-noise during class. A way around this limitation is, for instance, to use a sound lock (lobby) prior to classroom entry, to maintain elastic seals at door and window edge cracks, to supersede hollow core doors with solid doors, to use highly insulating double glazing, etc.

The above findings consist evidence that prefabricated concrete structures employing reusable elements, are capable of providing adequate sound insulation in school classrooms. Amongst other important factors with regard to construction detailing, it is indicated the importance of meticulous sealing at joints between prefabricated building elements.

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