Porous Concrete Road Pavements: Analysis of Noise Emissions and Applicative Implications from the Standpoint of both Active Safety and Freeze and Thaw Cycles Resistance

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Synopsis

Starting from previous studies carried out by the same Authors, this research is focused on the definition of the optimal mix design of a road pavement made of new draining porous concrete.
An accurate experimental investigation performed on different real-scale laying allowed the Authors to assess a series of structural and superficial characteristics of the road pavement above mentioned, so as to appreciate all its positive aspects, the perfectible ones being, in any case, highlighted.
In particular, apart from dealing with the mechanical strength of the structural elements against the passage of heavy vehicles and from assessing such parameters as superficial texture, permeability and porosity, the measurements were concentrated on the behavior of the elements themselves in case of very severe winter environmental conditions, with a special interest for freeze and thaw cycles as well as for the use of de-icing salts.
Furthermore, a special care was dedicated to the analysis of noise emissions connected with these new pavements, the measurements being taken by means of appropriate apparatus.
In addition, the research assessed the advantages from the standpoint of users safety belonging to the utilization of this structural elements: not only the spray, splash, aquaplaning and light reflection phenomena are dramatically reduced, but a significant decrease in the braking distance is observed for both dray and wet conditions.
Therefore, thanks to these remarks, the Authors believe that this innovative road pavements, if the perfectible aspects were faced, could be regularly used with positive implications for both users safety and environment protection.

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In this paper the Authors provided a further contribution to the topic, already faced in the recent past, of the definition of a porous concrete pavements which would guarantee, at the same time, positive structural performances and excellent characteristics from the standpoint of rainfall drainage [10], users safety [13] and environmental sustainability [15] [16].
In particular, with this research the mix design of the concrete matrix above mentioned was improved and any sort of enhancement from the point of view of noise emissions belonging to the application of this innovative superstructure was assessed.
Apart from this, the Authors aimed also at the evaluation of the increase of users safety as a consequence of the reduced braking distance, in an emergency situation, both in dry and wet conditions, connected with the porous concrete pavement.
Eventually, with a special interest in the use of these structural elements in mountainous areas, the last part of the investigation was concentrated on the assessment of the deterioration, if any, due to the use of de-icing salts in winter time, with respect to freeze and thaw cycles.

DATA ON THE PAVEMENT INVESTIGATED

The porous concrete pavement proposed by the Authors has a high void presence into the concrete matrix, which basically results from the definition of a particularly discontinuous grading curve.
Thanks to the optimization of the discontinuities of the particle size already investigated in previous experiences[3] the curve of Figure 1 was obtained.

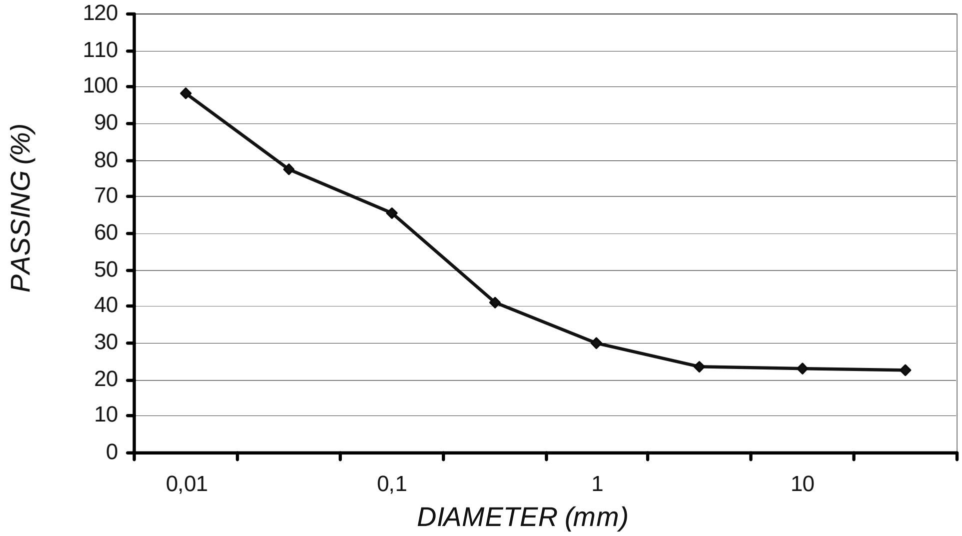

Fig. 1: Grading curve of the porous concrete pavement

In consequence of the mix design improvement, a 15x4 m experimental laying was poured (Figure 2) which, once finished off (Figure 3), was object of several tests by the Authors.
The complete pavement was manufactured by superposing a porous concrete layer onto a fibre reinforced concrete one with high mechanical properties, the reinforcing elements being copolymer and polypropylene fibres [2], [8], [9] (Figures 4 and 5).

Fig. 2: Manufacture of the concrete pavement **Fig. 3: Superficial finishing at the end of laying**

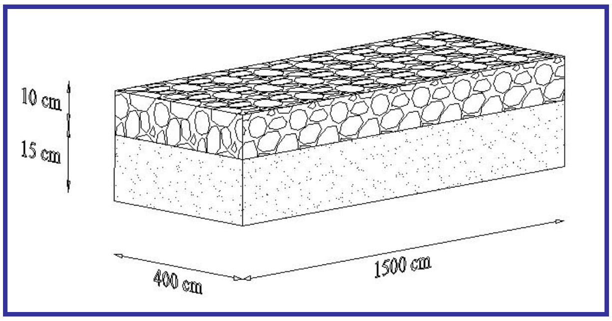

Fig. 4: Sketch of the pavement layers **Fig. 5: Superposition of the porous concrete layers**

Referring to the previous experiences on the subject [7],[5], the pavement was expected to show up significant performances from the point of view of both micro and macro-texture and, so as to confirm these opinion, some British Pendulum and Sand Height tests were performed.

Tables from 1 to 4 include, respectively, the micro and macro-texture outcomes, assessed in both areas where de-icing salts were or were not employed; with regard to that, only a marginal decrease in the overall performances was noticed in the area where calcium chloride was sprinkled, and this was important since some concerns arose before the execution of the tests: indeed, the question was if the calcium chloride would fill the voids, the final macro-texture being dramatically reduced.

Tab. 1: Micro texture results: porous concrete pavement exposed to de-icing salts

MICRO -TEXTURE					
Trial	**Measured value**	**MEAN BPN**	**Temperature °C**	**Corrective factor**	**FINAL MEAN BPN**
1	77	78	25	0	78
2	76			0	
3	78			0	
4	80			0	
5	79			0	

Tab. 2: Micro texture results: porous concrete pavement not exposed to de-icing salts

MICRO -TEXTURE					
Trial	**Measured value**	**MEAN BPN**	**Temperature °C**	**Corrective factor**	**FINAL MEAN BPN**
1	78	79	25	0	79
2	77			0	
3	81			0	
4	79			0	
5	80			0	

Tab. 3: Macro texture results: porous concrete pavement exposed to de-icing salts

MACRO-TEXTURE						
Trial	**D1 (mm)**	**D2 (mm)**	**Mean D (mm)**	**HS (mm)**	**Mean HS (mm)**	**Macro texture**
1	120	130	125	2,0	1,64	VERY COARSE
2	130	140	135	1,7		
3	150	160	155	1,3		
4	140	140	140	1,6		
5	140	140	140	1,6		

Tab. 4: Macro texture results: porous concrete pavement not exposed to de-icing salts

MACRO-TEXTURE						
Trial	**D1 (mm)**	**D2 (mm)**	**Mean D (mm)**	**HS mm)**	**Mean HS (mm)**	**Macro texture**
1	120	130	125	2,0	1,74	VERY COARSE
2	130	130	130	1,9		
3	140	140	140	1,6		
4	130	140	135	1,7		
5	140	150	145	1,5		

NOISE EMISSIONS ANALYSIS

The positive aspects of this kind of pavement from an environmental point of view was already remarked in literature [4], [11], the use of oil products being very reduced, especially if compared to ordinary bituminous elements.

In addition, one should consider that the high porosity of the concrete matrix should bring to a reduced level of noise emissions due to the cars passage on the surface [17].

As a matter of fact the very first aim of the research was concentrated on the understanding of how a manipulation of the grading curve, the material being the same (concrete), would affect the reduction of noise emissions, without employing any additional material in the paste or putting noise reducing barriers into place.

So as to get to an experimental evidence of this, during the investigation period several noise measuring at different speeds were performed, both inside and outside the vehicle, and the results of the porous concrete pavement were compared to the respective outcomes of a traditional concrete road superstructure.

For the sake of understanding, one should take into account that the outside measurements were directed towards the assessment of the environmental advantages, while the inside ones were mainly focused the attention on users comfort improvements.

The most sold economy car in Italy was employed for the purpose of the research on both pavements, in order to get to a relative comparison amongst the same results obtained on different surfaces, the driver, the driving aspects and the boundary conditions (gear, road section, engine emissions, etc) being unaltered (Figure 6).

Fig. 6: Measurement of noise emissions

Analysis performed outside the vehicle

The traveling velocity of the car was limited within the range 20-40 km/h in order to suppose an urban situation, the main field of use of such pavements being the reduced-speed areas [14].
The results of the external noise measurement test session performed on site are condensed in Tables 5-10.

Tab.5 Porous concrete pavement measurements at 20 Km/h

	1° measurement	2° measurement	3° measurement	Mean value
Laeq [dB]	55,8	56,9	56,7	56,47
LASMax[dB]	64,4	65,7	65,7	65,27
LASMin[dB]	45,7	45,7	45,7	45,70
Testing time	0.00.42	0.00.41	0.00.43	0.00.42

Tab.6 Normal concrete pavement measurements at 20 Km/h

	1° measurement	2° measurement	3° measurement	Mean value
Laeq [dB]	60,21	60,67	61,49	60,79
LASMax[dB]	70,63	71,11	71,57	71,10
LASMin[dB]	43,80	43,80	43,80	43,80
Testing time	0.01.15	0.01.18	0.01.24	0.01.19

Tab.7 Porous concrete pavement measurements at 30 Km/h

	1° measurement	2° measurement	3° measurement	Mean value
Laeq [dB]	57,8	58	58,1	57,97
LASMax[dB]	68,3	68,3	68,3	68,30
LASMin[dB]	45,7	45,7	45,7	45,70
Testing time	0.01.14	0.01.28	0.01.39	0.01.27

Tab.8 Normal concrete pavement measurements at 30 Km/h

	1° measurement	2° measurement	3° measurement	Mean value
Laeq [dB]	60,2	60,9	61,6	60,90
LASMax[dB]	70,8	73,8	75,5	73,37
LASMin[dB]	43,8	43,8	43,8	43,80
Testing time	0.01.29	0.01.39	0.01.46	0.01.38

Tab.9 Porous concrete pavement measurements at 40 Km/h

	1°measurement	2°measurement	3°measurement	Mean value
Laeq [dB]	58,6	59,3	59,9	59,27
LASMax[dB]	68,4	69,5	70,8	69,57
LASMin[dB]	45,7	45,7	45,7	45,70
Testing time	0.00.53	0.01.03	0.01.13	0.01.03

Tab.10 Normal concrete pavement measurements at 40 Km/h

	1° measurement	2° measurement	3° measurement	Mean value
Laeq [dB]	62,2	62,4	62,5	62,37
LASMax[dB]	75,5	75,5	75,5	75,50
LASMin[dB]	43,8	43,8	43,8	43,80
Testing time	0.00.53	0.01.02	0.01.05	0.01.00

In the following tables (11-12) the noise emission changes were compared to each other, with respect to different velocity variations Δv.

Tab.11: Porous concrete noise emissions variations as function of speed changes

Porous concrete pavement						
speed	**20**	**30**	**40**	**Δv (20-30)**	**Δv (30-40)**	**Δv (20-40)**
Laeq [dB]	56,47	57,97	59,27	1,50	1,30	2,80
LASMax[dB]	65,27	68,30	69,57	3,03	1,27	4,30
LASMin[dB]	45,70	45,70	45,70	0,00	0,00	0,00

Tab.12 Normal concrete noise emissions variations as function of speed changes

Normal concrete pavement						
speed	**20**	**30**	**40**	**Δv (20-30)**	**Δv (30-40)**	**Δv (20-40)**
Laeq [dB]	60,79	60,90	62,37	0,11	1,47	1,58
LASMax[dB]	71,10	73,37	75,50	2,27	2,13	4,40
LASMin[dB]	43,80	43,80	43,80	0,00	0,00	0,00

Analysis performed inside the vehicle

On the other hand, the results of the measurements performed inside the car, aiming at the assessment of the improvements, if any, of the users comfort, are included in Tables 13-14.

Tab.13 Noise emission inside the car for a porous concrete pavement at different speeds

Porous concrete pavement						
speed	**20**	**30**	**40**	**Δv (20-30)**	**Δv (30-40)**	**Δv (20-40)**
Laeq [dB]	63,03	63,30	63,50	0,27	0,20	0,47
LASMax[dB]	75,50	75,50	75,50	0,00	0,00	0,00
LASMin[dB]	43,80	43,80	43,80	0,00	0,00	0,00

Tab.14 Noise emission inside the car for a normal concrete pavement at different speeds

Normal concrete pavement						
speed	**20**	**30**	**40**	**Δv (20-30)**	**Δv (30-40)**	**Δv (20-40)**
Laeq [dB]	63,77	64,23	64,73	0,46	0,50	0,97
LASMax[dB]	75,50	75,50	75,50	0,00	0,00	0,00
LASMin[dB]	43,80	43,80	43,80	0,00	0,00	0,00

From the results obtained it is clear that, for low travelling velocities, the use of porous concrete pavements does permit a decrease in the noise emission belonging to tyres rolling on the surface, and these advantages are experienced both inside and outside the vehicle.

BRAKING DISTANCES ANALYSIS

Afterwards the investigation provided for the execution of several breaking tests, in order to assess to what extent the users safety could be improved thanks to the employment of such innovative pavements.
More specifically, two different kinds of cars were adopted for the purpose (sport car with ABS and economy car without anti blocking system), the measures being taken in both dry and wet surface conditions; the outcomes were compared to the corresponding results obtained for a traditional bituminous pavement manufactured in the same building site for the purpose, as illustrated in Figures 7 and 8.
All the tests were performed simulating a real emergency situation, with a full-push on the brake pedal. Obviously, the vehicle with ABS system never got to a skidding situation.
Tables 15-18 include the outcomes of this trial session.

Fig. 7: Economy car without ABS on porous concrete

Fig. 8: Sport Car with ABS on a bituminous pavement

Tab.15 : Braking distances on dry bituminous pavement: car with ABS

SKID TESTS (FIAT COUPE' WITH ABS)				
Kind of pavement	**Speed (km/h)**	**Trial**	**Breaking dist. (cm)**	**Breaking dist. mean value (cm)**
DRY BITUMINOUS PAVEMENT	40	1	310	337
		2	320	
		3	380	
	50	1	410	487
		2	500	
		3	550	
	60	1	550	593
		2	600	
		3	630	

Tab.16: Braking distances on dry bituminous pavement: car without ABS

SKID TESTS (FIAT PUNTO WITHOUT ABS)				
Kind of pavement	**Speed (km/h)**	**Trial**	**Breaking dist. (cm)**	**Breaking dist. mean value (cm)**
DRY BITUMINOUS PAVEMENT	40	1	530	590
		2	640	
		3	600	
	50	1	855	860
		2	860	
		3	865	
	60	1	1230	1287
		2	1260	
		3	1370	

Tab.17: Braking distances on dry porous concrete pavement: car with ABS

SKID TESTS (FIAT COUPE' WITH ABS)				
Kind of pavement	**Speed (km/h)**	**Trial**	**Breaking dist. (cm)**	**Breaking dist. mean value (cm)**
DRY POROUS CONCRETE PAVEMENT	40	1	290	295
		2	310	
		3	285	
	50	1	420	423
		2	430	
		3	419	
	60	1	518	520
		2	526	
		3	516	

Tab.18: Braking distances on dry porous concrete pavement: car without ABS

SKID TESTS (FIAT PUNTO WITHOUT ABS)				
Kind of pavement	**Speed (km/h)**	**Trial**	**Breaking dist. (cm)**	**Breaking dist. mean value (cm)**
DRY POROUS CONCRETE PAVEMENT	40	1	400	418
		2	380	
		3	475	
	50	1	619	614
		2	610	
		3	613	
	60	1	875	862
		2	851	
		3	860	

Subsequently the pavements were sprinkled with water (Figure 9) so as to assess the overall decrease of performances from the standpoint of breaking distances due to the presence of the water film on the pavement surface.

Fig. 9: the pavement sprinkled with water for the braking tests

The effects of these tests, carried out with the same vehicle as before, are contained in Tables 19-22.

Tab.19: Braking distances on wet bituminous pavement: car with ABS

SKID TESTS (FIAT COUPE' WITH ABS)				
Kind of pavement	**Speed (km/h)**	**Trial**	**Breaking dist. (cm)**	**Breaking dist. mean value (cm)**
WET BITUMINOUS PAVEMENT	40	1	385	390
		2	397	
		3	388	
	50	1	629	640
		2	641	
		3	650	
	60	1	968	955
		2	946	
		3	951	

Tab.20: Braking distances on wet bituminous pavement: car without ABS

SKID TESTS (FIAT PUNTO WITHOUT ABS)				
Kind of pavement	**Speed (km/h)**	**Trial**	**Breaking dist. (cm)**	**Breaking dist. mean value (cm)**
WET BITUMINOUS PAVEMENT	40	1	710	720
		2	730	
		3	720	
	50	1	983	980
		2	985	
		3	972	
	60	1	1501	1520
		2	1530	

		3	1529	

Tab.21: Braking distances on wet porous concrete pavement: car with ABS

SKID TESTS (FIAT COUPE' WITH ABS)				
Kind of pavement	**Speed (km/h)**	**Trial**	**Breaking dist. (cm)**	**Breaking dist. mean value (cm)**
WET POROUS CONCRETE PAVEMENT	40	1	302	299
		2	295	
		3	300	
	50	1	421	427
		2	428	
		3	432	
	60	1	530	533
		2	534	
		3	535	

Tab.22: Braking distances on wet porous concrete pavement: car without ABS

SKID TESTS (FIAT PUNTO WITHOUT ABS)				
Kind of pavement	**Speed (km/h)**	**Trial**	**Breaking dist. (cm)**	**Breaking dist. mean value (cm)**
WET POROUS CONCRETE PAVEMENT	40	1	426	422
		2	400	
		3	440	
	50	1	628	625
		2	620	
		3	627	
	60	1	879	877
		2	871	
		3	881	

The very first consideration after the execution of these tests is based on the fact that the porous concrete structural element, no matter the environmental conditions, the velocity and the type of vehicle, assured shorter braking distances, compared to a traditional bituminous pavement; the reason for this derived from the excellent superficial characteristics of such a pavement, which brought the tyre-pavement grip to the highest level possible.
Furthermore, in case of rainfalls the car without ABS experienced a decrease in the performances, the breaking distances being higher than the dry situations: while this phenomenon was particularly evident for the flexible pavement, the deterioration of the breaking quality was almost negligible for the porous concrete element.

Fig. 10 Calcium chloride used on the pavement

Fig.11: snowfalls on the pavement in winter time

ANALYSIS OF DE-ICING SALTS ATTACK

A 6 months period (autumn-winter) of investigation was considered for the carrying out of this test, and large quantities of calcium chloride (Figure 10) were sprinkled almost every day onto the concrete surface: in addition, the harmful effects of the salt were amplified by the continuous passage of heavy vehicle in both directions on the pavement.

The mountainous location of the site facilitated the test execution since, during the observation period, very frequent were the snowfalls in this area (Figure 11).

Fig.12: colorimetric test

Referring to the just mentioned Standards, at the end of the test the specimen should put on a dark colouring and, in case of chlorides penetration, the area affected by this phenomenon should take on a pink aspect.

At the end of the test there was no pink sign on the core sample, but only brown areas (Figure 13), which meant that no salts presence was discovered into the concrete specimen itself.

This test was performed for both halves of the pavement, just in case the salt solution seeped in through concrete, but the results did not change.

The Authors believe the reason for this was strictly connected with the high void ratio of the pavement, since the continuous vehicles passages, along with the intense winter rainfalls, activated a sort of self-washing process, the calcium chloride being expelled from the structural element.

Fig.13: results of the colorimetric test on the specimen

Furthermore, the visual analysis confirmed that no significant superficial degradation occurred after the prolonged and continuous action of salts intensified by the heavy vehicles pushing (Figure 14).
At the end of the research period it was found that, thanks to the initial superficial rolling and finishing off of the surface of the porous concrete pavement, performed in the same way of a bituminous binder, no structural deterioration was observed, validating the strong and perpetuated efforts on the study of the mix design of the concrete paste.

Fig.14: one of the heavy vehicle used to test the pavement

CONCLUSIONS

In this investigation the Authors studied the behaviour of a porous concrete pavement analysing, in particular, the reduction of the noise emissions coming from the tyres rolling on the surface and the braking distances variation in both dry and wet conditions; the outcomes, obviously were compared to the corresponding results of other typologies of pavements.
In addition, the efforts were also concentrated on the analysis of the de-icing salts attack and on the freeze and thaw resistance of the structural elements in severe winter conditions.
At the end of the research the following conclusions were found:

- The reduction of the external noise emissions of a porous concrete pavement, compared to a bituminous one, under urban velocity conditions varies within 2.9 and 4.3 dB. This outcome is even more significant if compared with the results the Authors found during a similar research on single and twin layer draining and noise reducing bituminous pavements, since the magnitude of the results is almost the same, no matter the two structural elements are completely different from the viewpoint of materials adopted;
- The comparison between the braking distance associated with a porous concrete and a bituminous pavement demonstrated that, in every condition, the first kind of superstructure drives to users safety improvements; in particular, higher are the differences between the braking distances of cars with and without ABS for bituminous pavements, and these remarks are much more amplified in case of wet surfaces;
- On the contrary, the excellent superficial features of the porous concrete structural element always guaranteed a proper grip to tyres, the situation seldom driving to tyres locking. This phenomenon was experienced also in wet conditions, and it was mainly due to the fact it was very hard to find a water film on the surface of the pavement with such a highly draining pavement;
- As for the salt attack and freeze and thaw cycles resistance, the behaviour of the porous concrete pavement was excellent; indeed, thanks to the high void ratio of the concrete matrix and to strong rainfalls, the passage of several heavy vehicles exalted the self-polishing features of the material, the calcium chloride being pushed away from the pavement itself.

In conclusion the results of the investigations performed so far on these innovative road superstructures are reassuring from every point of view: the mechanical resistance was already assessed in the past [6], [12], while the salt penetration in case of freeze and thaw cycles was appraised during this research, with positive conclusions.
Last but not least, positive were also the consequences of the noise emission analysis in every conditions from the standpoint of the environmental friendliness of the new pavement, as well as the outcomes based on users safety consideration: as a consequence this investigation do encourage further studies on the matter, which should be mainly addressed on a fresh improvement of the aggregates self-blocking.

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