In-Situ Mechanical Characterization of Waste Tire Rubberized Concrete (PFU) for Airport Pavements

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SUMMARY. In this study, the results of an in-situ experimental program on the performance of concrete taxiways are presented. The experimental program has been undertaken at the Guglielmo Marconi airport of Bologna (Italy). It concerns two portions of the taxiway, one realized in plain concrete and one realized in rubberized concrete. Each portion has been instrumented with strain gauges for the acquisition of vertical strains inside concrete.

1 INTRODUCTION

Rubberized concrete is obtained by replacing a part of the fine or coarse aggregate with rubber scraps. This gives rise to a concrete with low unit weight, high toughness, high impact resistance and increased deformability or ductility.

One of the most interesting rubberization techniques of concrete as far as the recycling of waste materials is concerned is the use of grinded discarded tires. Waste tires are a major concern among the waste materials, as the amount of waste tires is increasing more and more due to the increasing demand for tires and because of their short lifetime. They have hardness and elasticity properties superior to those of rubber. Moreover, they can be used in almost any environmental conditions and in any climate due to their good resistance to weathering, ability to withstand both hot and cold, anti-caustic and anti-rot properties.

In last 20 years, several researchers have investigated the changes of strength, workability and dynamic characteristics of rubberized concretes in terms of size and amount of rubber scraps and rubber types [1]-[12]. It was found that rubberized concrete is an ideal material for all those structural members which are subjected to immediate effects of impact and for which desired deformability or toughness is more important than strength, such as jersey barriers, road foundations and bridge barriers. In particular, rubberized concrete has shown to be able to absorb the impact energy and reduce or minimize vibration more efficiently than traditional concrete is.

Since a material with high plastic energy could show higher deformation at the time of fracture and absorb more energy, with the plastic energy capacities enhanced, the idea underling the present investigation is that the rubberized concrete could be used in airport pavements, in order to delay cracking and increase the skid resistance of concrete runways. By absorbing the impact energy, this material could also prevent eventual damages to aircraft undercarriages when landing.

2 AIRPORT PAVEMENTS

An airport pavement is a structure consisting of one or more layers placed on a prepared sub-grade. Pavements must be designed in such a way that they can bear the loads imposed by aircraft without failure. A pavement must be smooth and stable under conditions of loading during its expected or economic life. It must be capable of spreading and transmitting an aircraft weight to the existing sub-soil (or sub-grade) in a manner that precludes subsoil failure. Another function of the pavement is to prevent weakening of the subsoil by moisture intrusion, especially from rainfall and frost.

Pavement performances are especially sensitive to the frequency of loadings. Areas subjected to repeated loadings due to concentration of traffic must be designed to accommodate the stresses arising from such loadings. The repetition of load by heavy vehicle will contribute cumulative damage over the life of the pavement. The repetition is much smaller over airport runways and taxiways than highways, but the involved weights are greater for airport pavements. The major distresses on airfield pavements are caused from slow moving loads on the taxiways and ends of runways. The ends of the runway are also involved by static load condition coupled with vibration, due to running up the engines of jet aircraft to develop full thrust. This imposes high stress concentrations in the pavement.

Due to different gear assemblies the critical positions are not equally loaded by all aircrafts. Aircrafts can have two or more landing gears at different positions from the body of the aircraft. Furthermore, all movements of one aircraft, like starting and landing, do not occur at the same position. The position of landing, for example, is influenced by the pilots accuracy, cross wind, width of runway etc. This phenomenon is called lateral wander and is normally simplified by dividing all movements into a normal distribution around the centerline marking on the pavement.

Lateral wander has an important influence on the rutting performance of pavements, since individual aircraft wander patterns create traffic lanes. Three basic approaches are in use in the United States to account for traffic wander [13]: the Asphalt Institute Method, the Portland Cement Association Method and the Corps of Engineers Method. In the third method, the lateral distribution of traffic is assumed to be uniform within a certain design Traffic Lane, in contrast to a normal distribution. All the methods agree in assessing to taxiways a traffic channelization degree higher than that of runways. The traffic is highly channelized also on runway ends and turnoff areas from the runway to the taxiway or to the apron area.

The wander width is defined by the zone containing 75% of the aircraft centrelines (1.15 standard deviations on either side of the mean value with a normal distribution). Data collected in the 1970's indicate wander widths of $1778\ mm$ for taxiways and $3556\ mm$ for runways. The standard deviation was found as $775\ mm$ for a taxiway and $1524\ mm$ for a runway [14]. It is not only individual aircraft wander that affects pavement performance. Each aircraft has a unique gear configuration and different combinations of aircraft will induce additional wander that is not associated with lateral deviation of individual aircraft.

Also the sizes and the numbers of airplanes, as well as the introduction of large and heavy aircraft and changes in wheel loads and tire pressures significantly affect the pavement performance. Finally, in cases where the pavement is particularly rough it can accelerate aircraft fatigue from both the dynamic response of the aircraft as well as accelerated loading on the pavement.

On the basis of the common anticipated distress, the airfield areas are categorized into four so called traffic areas, to which any airfield design must attain.

There are two types of airfield pavements, rigid and flexible pavements. Flexible airfield pavement is a structure composed of several layers of material placed on a sub-grade, each of which receives the loads form the above layer, spreads and distributes them out, then passes them on the layer below [15]. The further down in the pavement structure the layer is, the fewer loads it must carry.

Flexible airport pavement typically consists of four layers:

- Bituminous surface course;
- Base course;
- Sub-base course;
- Sub-grade course.

In particular, the surface course usually consists of two layers: the wearing course, at the top, and the binder course, at the bottom.

Rigid airport pavement consists in a slab of Portland cement concrete that rests on a subgrade or subbase. Relatively thin sub-bases may be placed under rigid pavements to prevent pumping and also improve a low strength sub-grade. Due to its higher stiffness, the rigid pavement is recommended in those areas where the distress danger is higher and/or the traffic is highly channelized and where live loads concentrate over longer periods of time (apron and associated service road), in order to avoid wheel ruts due to repeated tracking of aircraft and equipment. On the aprons and at runway ends, where aircrafts stand, the use of concrete pavements is to be preferred to asphalt also because fuel spillage is frequent in those areas and the asphaltic concrete is vulnerable to damage by aviation fuel.

3 EXPERIMENTAL SET-UP

The experimentation has been carried out on a 14 *m* length segment of the taxiway of the Guglielmo Marconi airport (Bologna, Italy), which is a flexible pavement taxiway.

A taxiway is a specially prepared or designated path on an airfield, other than apron areas, on which aircrafts move under their own power to and from landing, service, and parking areas (taxiing). Since planes have no motors for their wheels, the shear stresses arising in airfield pavements from the friction between the pavement and the aircraft wheels are opposite to those developed by cars. The involved friction is a rolling resistance friction. Actually, instead of pushing against the ground to produce its thrust, an airplane pushes against the air using a propeller or jet engine. By pushing air backwards, the planes pushes itself forward in accordance with Newton's Third Law of Motion. The wheels are present not to provide a means of propulsion but to reduce the friction between the airplane and the ground, thus increasing net thrust.

Table 1: Cross-sections of the taxiway flexible and rigid pavements.

	Flexible pavement	Section 1 rigid pavement	Section 2 rigid pavement
Wearing course	4 *cm*	4 *cm*	4 *cm*
Binder course	6 *cm*	/	/
Base course	10 *cm*	/	/
Plain concrete slab	/	16 *cm*	/
Rubberized concrete slab	/	/	16 *cm*
Sub-base course	50 *cm*	50 *cm*	50 *cm*
Sub-grade course	30 *cm*	30 *cm*	30 *cm*

The experimental segment was divided into two sections of 7 *m* each, to be realized with rigid pavement. The taxiway rigid and flexible pavements share the same sub-base, sub-grade and wearing courses. In the rigid pavement, the base and binder courses of the flexible pavement were substituted with a slab of plain concrete, in the first section, and rubberized concrete, in the second section. The thicknesses of the several layers of the three pavements are collected in Table 1. Note how the thickness of the concrete slab is less than one half the slab thickness of a rigid pavement

($40 \div 50$ cm), both for Section 1 and 2.

The two sections were instrumented with strain gauges embedded in concrete. The strain gauges were positioned along two transverse sections, one for each section of rigid pavement, so as to acquire the vertical strains due to wheel loads. Only one half of each transverse section was instrumented. The strain gauges were positioned just below the upper bound of the concrete slabs.

As said in §2, the taxiway is an area of highly channelized traffic, due to its low wander width. This configures the taxiway as an optimum area for the experimental analysis of distresses due to repeated loads. Moreover, the high channelization allowed us to identify with a good degree of precision the transverse gear wheel locations for various aircrafts. It was found that five equally spaced locations covers 74% of the annual traffic of the Guglielmo Marconi airport. They are spaced for intervals of 43.5 cm, with a distance between the centre line and the closer location of 221 cm. Figure 1 shows five of the ten used strain gauges (five for each section), settled out to be embedded under the five equally spaced lanes. The strain gauges were connected to a real-time controller, which also allows remote data acquisition.

Figure 1: Positioning of the strain gauges over the metal support.

4 MIX-DESIGN AND PROPERTIES OF THE FRESH CONCRETE

The two concrete mixtures used in the experimentation share the same type of binder (Portland II AL 45.5R Micronmineral), alluvial coarse aggregates ($8 \div 15$ mm) and fine aggregates (sand of $0 \div 5$ mm and Po sand of $0 \div 2$ mm).

A finer kind of fine aggregates, Po sand, was added to sand since the gradation analysis of the employed sand had shown a poor content of fine fractions. This follows in a high Fineness Modulus (FM) of fine aggregates when only sand is used. Fineness Modulus is an empirical number relating to the fineness of the aggregate, used in determining the degree of uniformity of the aggregate gradation. The derivation of this parameter was based on using only a single parameter for describing a grading curve. The higher FM, the coarser the aggregate. The fineness Modulus is defined as the sum of the cumulative percentages retained on specified sieves divided by 100:

$$FM = \frac{\Sigma\left(\text{cumulative percentage retained on specified sieves}\right)}{100}. \quad (1)$$

In literature various authors suggest the derivation of Fineness Moduli. The all vary regarding their derivation from one to the other. Well-known examples of such measures are the FM from Abrams [16]-[17], Faury's "l'indice pondéral" [18], the F-value from Hummel [19], Spindel's R-value or the "Kornpotenz" (grain power) from Stern [20]. The latter all being variants of Abrams' FM. According to EN 12620, sand FM is calculated here as the summation of the oversize material (in Vol.-%) of the $4\,mm$, $2\,mm$, $1\,mm$, $0.5\,mm$, $0.25\,mm$ and $0.125\,mm$ sieves divided by 100:

$$FM = \frac{\Sigma\{(>4)+(>2)+(>1)+(>0.5)+(>0.25)+(>0.125)\}}{100} = 3.52\,. \tag{2}$$

The value provided by (2) is high due to the passing's poor sand content through the $0.25\,mm$ and $0.125\,mm$ sieves. Moreover, sand gradation does not satisfy the ASTM requirement of having a passing of $10\div30\%$ through the $0.3\,mm$ sieve and $2\div10\%$ through the $0.15\,mm$ sieve, following in a grading curve that slightly outgoes the ASTM upper bound limit curve (ASTM C 33-71 a).

Po sand is a very fine monogranular aggregate ($FM = 1.97$) with 85% of the gradation included between $0.1\,mm$ and $1\,mm$. In order to decrease the cumulative FM of natural fine aggregates in the rubberized mixture, sand was mixed in 79.5 Vol.-% (ssd) with Po sand for the remaining 20.5 Vol.-% (ssd). Adding Po sand leads to a fine aggregates gradation with a passing of 18% through the $0.3\,mm$ sieve and 5% through the $0.15\,mm$ sieve. Moreover, the cumulative grading curve of fine aggregates lies between the two ASTM limit bound curves.

In the control mixture, a percentage of 85.4 Vol.-% (ssd) of sand and 14.6 Vol.-% (ssd) of Po sand was sufficient to match ASTM requirements.

The rubber aggregates were obtained by mechanical grinding of tires, without any kind of purification. Therefore, they may contain small amounts of steel and textile fibers. According to previous studies [21]-[22], aiming at evaluating the optimum amount of tyre rubber that can be substituted to sand thus avoiding severe loss of compressive strength, we chose here to use a 22 Vol.-% substitution percentage. The rubber aggregates were substituted to sand since it was found [21]-[22] that the best results for workability and mechanical strength were obtained when sand fraction, and not fine filler fraction, was replaced by tyre waste of similar grain size. A $1\div2.4\,mm$ rubber aggregate was employed here.

Once we defined the fine aggregate composition, the amount of coarse aggregate has been computed according to the Füller grain size distribution. The cumulative aggregate FM (coarse aggregates + fine aggregates) for rubberized concrete is equal to 5.22.

In the following, the control and the rubberized mixture will be named Mixture 1 and Mixture 2, respectively. The aggregate composition of the two mixtures is shown in Table 2, where all the percentages are computed in the assumption of saturated surface dry condition (ssd).

Table 2: Aggregate composition in saturated surface dry condition (ssd).

	Mixture 1		Mixture 2	
	Weight%	Volume%	Weight%	Volume%
Coarse aggregates	51.9%	52.0%	53.1%	50.0%
Sand	41.0%	41.0%	33.0%	31.0%
Po sand	7.1%	7.0%	8.6%	8.0%
PFU	/	/	5.3%	11.0%

Coarse and fine natural aggregates and rubber aggregates (only for Mixture 2) were fed into the concrete mixer in this order and mixed for 5 min. The cement was then added and mixed with aggregates for 2 min. more. Finally, 75% of the water and the admixture with the remaining water were added and mixed for 10 min.

The workability of the fresh concrete was assessed with the Abrams slump test, undertaken in accordance with UNI 9418 and UNI EN 12350-2. For both mixtures, the desired consistency of fresh concrete was the S5 consistency class, the super fluid class (UNI EN 206-1:2006, UNI 11104:2004), with a target slump of $220 \pm 30\ mm$ (according to UNI EN 206-1:2006, the tolerance applied to a target slump $\geq 100\ mm$ is $\pm 30\ mm$). To reach a super fluid consistency, a considerable amount of water is required. This leads to a decrease of strength and resistance to frost and aggressive environments in hardened concrete and an increased danger of segregation and bleeding. In order to reach a super fluid consistency without exceed in quantity of water, we have used a polyacrylic superplasticizer admixture (Axim Creactive LX fluxing agent) for an amount of 0.65% in relation to the cement mass in Mixture 1 and 0.8% in Mixture 2. This allowed a water reduction by 16% for Mixture 1 and 21% for Mixture 2. The slump was $220\ mm$ for Mixture 1 and $215\ mm$ for Mixture 2, thus matching the target slump in both cases.

5 EXPERIMENTAL RESULTS

5.1 *Laboratory tests on hardened concrete*

According to UNI EN 206-1:2006, the hardened concrete is classified on the basis of the value assumed by ρ, the volumic mass or density, after oven-drying (EN 12390-7):

- Light-weight concrete, if ρ ranges between 800 and 2000 kg/m^3;
- Normal-weight concrete, if ρ ranges between 2000 and 2600 kg/m^3;
- Heavy-weight concrete, if ρ is greater than 2600 kg/m^3.

The oven-dry density of Mixture 2, computed as mean value evaluated on two cubic specimens of 15 cm side each, is intermediate between that of a normal- and light-weight concrete:

$$\rho = 1976\ kg/m^3, \tag{3}$$

with a water absorption by immersion (EN 1097-6, UNI 7699), expressed as the water uptake relative to the oven-dry mass, equal to:

$$W = \frac{M_{ssd} - M_{dry}}{M_{dry}} = 7.62\%, \tag{4}$$

where M_{ssd} is the saturated surface dry mass and M_{dry} is the oven-dry mass. The value provided by (4) is slightly smaller than the water absorption by immersion of Mixture 1.

After uniaxial compression test, the specimens prepared with Mixture 2 appeared to have a very good distribution of the rubber aggregates in the cement paste and did not show any signs of segregation.

Figure 2 shows the stress-strain relationships for two specimens prepared with Mixture 1 and 2, respectively. The 28 days mean compressive strengths and elastic modules for Mixture 1 and 2 (averaged over 3 specimens) are collected in Table 3.

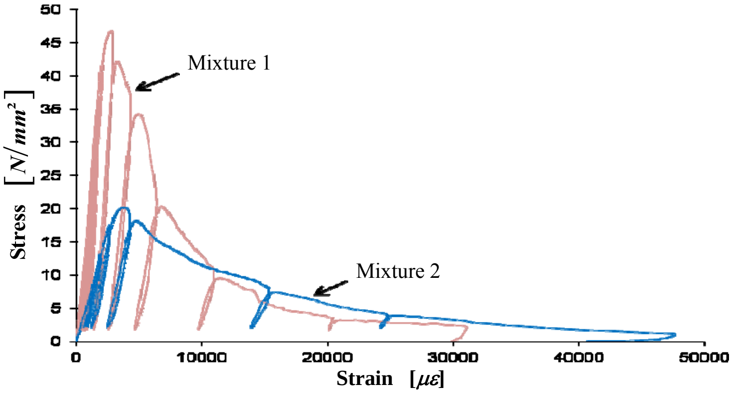

Figure 2: Stress-strain relationships for the two mixtures.

Table 3: Mechanical properties of Mixture 1 and 2 after 28 day curing (UNI 6126, UNI 6127, UNI 6130/I, UNI 6130/II, UNI 6132, UNI 6556:1976).

Mixture 1		Mixture 2	
Compressive strength $\left[N/mm^2\right]$	Elastic modulus $\left[N/mm^2\right]$	Compressive strength $\left[N/mm^2\right]$	Elastic modulus $\left[N/mm^2\right]$
46.65	18070	20.10	5001

5.2 *In-situ data acquisition*

Results concerning the strain and stress profiles along the two instrumented cross-sections when the gear wheels stand over them are here presented. The two curves in Figure 3 interpolate the strains acquired on the two cross-sections.

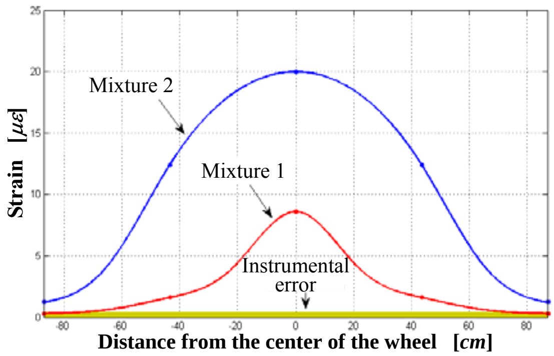

Figure 3: Acquired data and interpolation curves for the strains in plain and rubberized concrete.

While strains are higher for Mixture 2 than for Mixture 1, when identifying the cross-sections stresses in the first-order approximated uniaxial assumption:

$$\sigma = E\varepsilon , \tag{5}$$

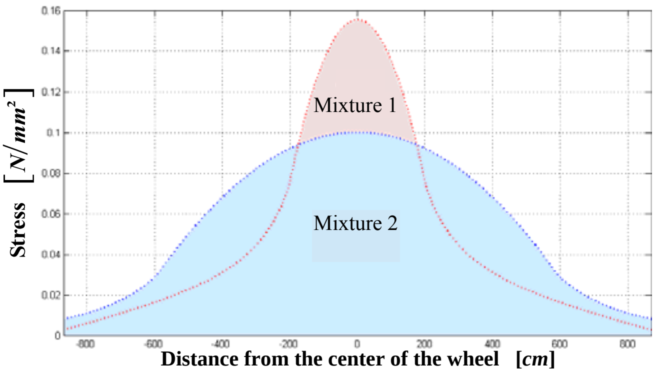

Figure 4: Identified stresses in plain and rubberized concrete.

we find that the maximum achieved stress is lower in Mixture 2 than in Mixture 1 (Figure 4). This happens since the ratio between the elastic modulus of Mixture 2 and 1 is lower than the ratio between the strains of Mixture 1 and 2. One of the main consequences is that the stress field depends on the elastic properties of the mixture (Young's and Poisson's modules). This is a remarkable result, since it contradicts the Boussinesq's closed form solution for a homogeneous, linear-elastic, and isotropic half-space subjected to a point-load perpendicular to the surface [23]. Actually, Boussinesq found a vertical stress σ_v depending on the distance r between the application and the evaluation points and the angle θ between the point load vector and the radial arm connecting the application to the evaluation point only:

$$\sigma_v = \frac{3}{2}\frac{P}{\pi r^2}\cos^3\theta\,, \tag{6}$$

where P is the point load applied at the surface.

Neither in the equation of Fröhlich [24], which is an extension of that of Boussinesq to the case of a granular medium, the vertical stress is an explicit function of the elastic modules:

$$\sigma_v = \frac{n}{2}\frac{P}{\pi r^2}\cos^n\theta\,, \tag{7}$$

where n is the Fröhlich's stress concentration factor and depends on the medium properties. With $n = 3$ one obtains the Boussinesq's equation.

It is worth noting that, using $n = 2$, the Fröhlich's equation gives the classic CBR (California Bearing Ratio) equation [25]. The CBR method was developed in the 40's for the design of flexible pavements to support heavy bombers and is currently in use in the U.S. Military (Army, Air Force and Navy) as design procedure for flexible airport pavements.

The lower maximum stress achieved in Mixture 2 gives rise to a stress curve smoother than that of Mixture 1 (Figure 4). This follows in lower stress gradients for Mixture 2 than for Mixture 1. Since an high stress gradient is one of the main causes of distresses for repeated loads, it is reasonable to aspect a longer economic life for Mixture 2 than for Mixture 1.

From Figure 4 we can also appreciate that the two curves intersect, following in a greater stressed area when Mixture 2 is used instead of Mixture 1. This behavior matches the vertical equilibrium requirement. Actually, the area below the two curves must be the same since this area shows the applied load, equal in both cases. The difference between the two areas in Figure 4 is negligible if we consider the error introduced in approximating the triaxial state of stress with a uniaxial one (Eq. 5) and the further error due to a finite extension of the instrumented field, smaller than the stressed field.

The conservation of the equilibrium gives validity to the identified data and the related discussions, included the one on the Boussinesq theory.

6 CONCLUSIONS

A new type of airfield pavement has been proposed here, intermediate between a flexible and a rigid one. A rubberized cement concrete mixture has been used for preparing a concrete slab, typical of a rigid pavement, but the sub-base and sub-grade courses are those typical of a flexible pavement and the concrete slab thickness is much smaller than that of a rigid pavement. The experimental results have been compared with those of an analogous pavement that differ from the previous one for the concrete mixture only, a control plain concrete mixture.

The in-situ real-scale experimentation has shown that rubberized concrete is more effective than plain concrete in spreading the applied load and distributing it over a large area of the concrete slab / sub-base course interface. Since a larger stressed area involves a lower mean stress, this means that the sub-base works at lower levels of stress with a rubberized than a plain concrete slab over it. This allows us to better exploit the strength properties of the sub-base course.

The experimental results also exhibit a dependence of the vertical stresses on the elastic properties of the concrete slab, which is not accounted by neither the Boussinesq's findings nor the modified closed solutions of the elastic problem in half-spaces subjected to a point load. Since the experimental results seem to be realistic, due to the fact that they satisfy equilibrium, this indicates that the Boussinesq elastic solution must be carefully revised [26], looking for a higher order solution that also allows us to evaluate the role played by the Young's and Poisson's modules.

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References

[1] Bignozzi, M.C. and Sandrolini, F., "Tyre rubber waste recycling in self-compacting concrete", *Cement Concrete Res.*, **36**, 735-739 (2006).

[2] Fattuhi, N.I. and Clark, L.A., "Cement-based materials containing shredded scrap truck tyre rubber", *Constr. Build. Mater.*, **10(4)**, 229-236 (1996).

[3] Fedroff, D., Ahmad, S. and Savas, B.Z., "Mechanical properties of concrete with ground waste tire rubber", *Transportation Research Board 1996; Report No. 1532*, 66-72 (1996).

[4] Ghaly, A.M. and Cahill IV, J.D., "Correlation of strength, rubber content, and water to cement ratio in rubberized concrete", *Can. J. Civil. Eng.*, **32(6)**, 1075-1081 (2005).

[5] Hernandez-Olivaresa, F., Barluenga, G., Bollatib, M. and Witoszek, B., "Static and dynamic behaviour of recycled tyre rubber-filled concrete", *Cement Concrete Res.*, **32(10)**, 1587-1596 (2002).

[6] Khatib, Z.K. and Bayomy, F.M., "Rubberized Portland cement concrete", *J. Mater. Civil. Eng.*, **11(3)**, 206-213 (1999).

[7] Li, G.Q., Stubblefield, M.A., Gregory, G., Eggers, J., Abadie, C. and Huang, B.S., "Development of waste tire modified concrete", *Cement Concrete Res.*, **34(12)**, 2283-2289

(2004).
[8] Naik, T.R. and Siddique, R., "Properties of concrete containing scrap tire rubber – an overview", *Waste Manage*, **24(6)**, 563-569 (2004).
[9] Topçu, İ.B., "The properties of rubberized concretes", *Cement Concrete Res.*, **25(2)**, 304-310 (1995).
[10] Wang, Y., Wu, H.C. and Li, V.C., "Concrete reinforcement with recycled fibers", *J. Mater. Civil. Eng.*, **12(4)**, 314-319 (2000).
[11] Yang, H.S., Kim, D.J., Lee, Y.K., Kim, H.J., Jeon, J.Y. and Kang, C.W., "Possibility of using waste tire composites reinforced with rice straw as construction materials", *Bioresource Technol.*, **95**, 61-65 (2004).
[12] Zheng, L., Sharon Huo, X. and Yuan, Y., "Experimental investigation on dynamic properties of rubberized concrete", *Constr. Build. Mater.*, **22**, 939-947 (2008).
[13] Yolder, E.J, Witczak, M.W., *Principles of pavement design*, John Wiley & Sons, Inc., New York (1975).
[14] Ho Sang, V.A., "Field survey and analysis of aircraft distribution on airport pavements", Report No. FAA-RD-74-36. U.S. Federal Aviation Administration (1975).
[15] Wei, V.N.Y., *The development of airside infrastructure at the Senai International Airport: a case study*, PhD thesis, Faculty of Civil Engineering, Universiti Teknologi Malaysia (2009).
[16] Abrams, D.A., "The basic principles of concrete mixes", *Mining and Scientific Press*, 23-24 (1918).
[17] Abrams, D.A., *Design of Concrete Mixtures,* Bulletin 1, Structural Materials Research Laboratory, Lewis Institute, Chicago, 1-22 (1918).
[18] Faury. J., *Le béton: influence des constituants inertes. Régles à adopter pour sa meilleure composition, sa confection et son transport sur les chantiers*, *Etudes de synthèse et de documentation*, Dunod, Paris, (1958).
[19] Hummel, A., *Das Beton – ABC – Ein Lehrbuch der Technologie des Schwerbetons und des Leichtbetons*, 11th edn, Wilhelm Ernst & Sohn, Berlin (1959).
[20] Stern, O., "Vorschlag für eine Norm: Kornpotenz (Feinheitsmodul) loser Haufwerke", *Sparwirtschaft*, **4**, in German (1932).
[21] Bignozzi, M.C. and Sandrolini, F., "Recycling tyre rubber in building materials", in Proc. *Sustainable Waste Management and Recycling: Used/Post-Consumer Tyres* (Thomas Telford, London, 2004), Kingston University, London, September 14–15, 2004, 77-84 (2004).
[22] Bignozzi, M.C. and Sandrolini, F., "Il riciclo di pneumatici particellati come aggregati fini in malte cementizie autocompattanti", in Atti dei *Seminari di Ecomondo 2005* (Maggioli Editore, 2005), Rimini, 26-29 Ottobre, 2005, 41-46 (2005).
[23] Boussinesq, M.J., *Application des potentiels a l'étude de l'équilibre et du mouvement des solides élastiques, avec des notes étendues sur divers points de physique mathématique et d'analyse*, Gauthier-Villars imprimeur libraire, Paris (1885).
[24] Fröhlich, O.K., *Druckverteilung im Baugrunde*, Springer Verlag, Wien (1934).
[25] Gonzales, C.R., "Implementation of a New Flexible Pavement Design Procedure for U.S. Military Airports", in Proc. *Fourth LACCEI International Latin American and Caribbean Conference for Engineering and Technology – LACCEI'2006*, Mayagüez, Puerto Rico, 21-23 June, 2006, 10 pp. (2006).
[26] Ferretti, E., "A Higher Order Solution of the Elastic Problem of Boussinesq for an Homogeneous, Linear-Elastic, and Isotropic Half-Space Subjected to a Point Load", in preparation.