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Ecological and mechanical assessment of lightweight fiber-reinforced concrete made with rubber or expanded clay aggregates

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HIGHLIGHTS

- Rubber granulates is used herein to cast an eco-friendly lightweight concrete (RLC).
- RLC is compared with a traditional lightweight concrete with expanded clay (TLC).
- The results of the eco-mechanical analyses depend on the chosen functional unit.
- When compressive strength is the functional unit, TLC shows the best performances.
- Referring to a structural parameter, the use of RLC plates is more convenient.

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ABSTRACT

To reduce the environmental impact of traditional lightweight concrete (TLC), porous aggregates can be substituted by rubber granulates. The mechanical properties of such rubber lightweight concrete (RLC) are investigated and compared with those of TLC made with expanded clay aggregates. Uniaxial compression and three point bending tests were performed for assessing the mechanical and ecological performances of the two mixtures, containing or not plastic fibers. As a result, when compressive strength is the functional unit of the analyses, TLC performs better than RLC. Conversely, fiber-reinforced RLC is the best solution when flexural strength and structural ductility are the required performances.

1. Introduction

According to the definition given by Model Code 2010 (MC2010) [1], the density of lightweight aggregate concrete varies from 800 to 2000 kg/m^3. To reduce the mass of normal weight structural concrete, stone aggregates are substituted by cellular structured particles. Such lightweight aggregates are generally produced by heating some raw materials (e.g., shale, clay, slates, fly ashes, etc.) to incipient fusion, and then cooling them in the so-called pyroprocessing method [2].

Lightweight concretes are mainly used to reduce the mass, and consequently the dead loads and the inertial seismic actions, of both new and existing structures, and to facilitate transportation and placement of precast elements. In general, to justify the use of lightweight concrete, which is more expensive than normal weight concrete, a lower cost of the project and/or an improved functionality must be attained [2]. This is the case of the precast plates proposed by Fantilli et al. [3] for the sidewalks of an existing bridge. Specifically, a lightweight concrete with expanded clay aggregates was tailored to facilitate the lift of the plates, which were reinforced with plastic fibers in place of the traditional steel rebar.

With respect to this solution, a more environmental-friendly lightweight concrete can be realized by using rubber from end-of-life tires as non-conventional aggregate [4,5]. Indeed, also the density of rubber granulates (with the dimensions of grains comprised between 0.8 and 20 mm [6]) is lower than that of the stone aggregates. The use of rubber in the concrete industry is also convenient from an environmental point of view. Specifically, hundreds of millions scrap-tires are generated each year worldwide, and their landfilling is becoming unacceptable due to the rapid depleting of the sites and to the associated environmental risks [4].

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Notations

b	width of a plate cross-section
EI	ecological index
E_{lc}	tangent modulus of elasticity experimentally evaluated in lightweight concrete
E_{lci}	average value of the tangent modulus of elasticity of lightweight concrete estimated in accordance with MC2010 [1]
E_{lc1}	secant modulus from the origin to the peak of stress of lightweight concrete [1]
f_{lc}	compressive strength of lightweight concrete
$f_{lct,fl}$	flexural tensile strength of lightweight concrete
h	depth of a plate cross-section
k_{lc}	plasticity number of lightweight concrete [1]
l	span of a plate in three point bending
M_{cr*}	bending moment at the effective cracking of a plate
MI	mechanical index
P	load applied to a plate in three point bending
P_{cr*}	effective cracking load of a plate in three point bending (Fig. 6)
P_d	design load acting on a plate in three point bending [1]
P_u	ultimate load of a plate in three point bending (Fig. 6)
Q_f, $Q_{f,min}$	fiber content of a plate in three point bending and its minimum value [13]
r	flexural/compressive strength ratio of a lightweight concrete
W	section modulus of a plate
α	quantity of carbon dioxide (CO_2) released by concrete components
β	quantity of embodied energy used by concrete components
γ_G	partial safety factor for permanent actions [1]
γ_Q	partial safety factor for variable actions [1]
δ	midspan deflection of a plate in three point bending
δ_{cr*}	midspan deflection associated to P_{cr*} of a plate in three point bending (Fig. 6)
δ_u	midspan deflection associated to P_u of a plate in three point bending (Fig. 6)
ε	compressive strain
ε_{lc1}	strain at the maximum stress of lightweight concrete
σ	compressive stress

Nevertheless, the presence of rubber reduces the compressive strength of concrete, as evidenced in several studies [4,5]. Concrete class reduces with the content of rubber, and sometimes becomes lower than the minimum values required for structural uses. Moreover, compressive strength is generally assumed to be the functional unit of concrete, to which the inputs and outputs of a lifecycle assessment must be referred [7]. As high-strength concretes are in principle better than normal-strength concretes from an ecological point of view [8], traditional lightweight concrete (TLC) should also be more environmental-friendly than rubber lightweight concrete (RLC).

Despite that, in several applications, the functional unit must take into account more than the mere compressive strength. For instance, to achieve the best eco-mechanical performances of high-strength but brittle concretes, material ductility needs to be enhanced [9]. In addition, in beams and plates subjected to bending actions, tensile (or flexural) strength and fracture toughness are the most important properties. Without modifying the compressive strength, the bending capacity of these structures, and the fracture toughness of the concrete as well, can be increased if fibers are added to the cementitious matrix [10,11].

Accordingly, a more comprehensive analysis, including the environmental impact and the mechanical behavior of plain and fiber-reinforced concrete, needs to be applied to full-scale structures. Since a direct comparison between the material and structural performances of TLC and those of RLC cannot be found in the current literature, the present paper aims at filling this gap. Specifically, concrete cylinders and full-scale one-way plates were tested in uniaxial compression and three point bending, respectively. Although TLC and RLC mixtures can lead to different compressive strength, they were accurately tailored in order to behave in the same way under bending actions [3]. Hence, the measured eco-mechanical performances of the lightweight concrete mixtures, some reinforced with short plastic fibers, can be compared with respect to different functional units.

2. Experimental investigation

2.1. Concrete mixtures

Three TLC mixtures, named TLC_0, TLC_7 and TLC_10 and made with expanded clay aggregates, are taken into consideration (see Table 1). Such concretes, used for the maintenance of a bridge [3], are plain (TLC_0) and fiber-reinforced (TLC_7 e TLC_10). More precisely, a cubic meter of the mixtures TLC_7 and TLC_10 is respectively reinforced with 7 kg and 10 kg of short plastic fibers (diameter = 0.48 mm, length = 54 mm, elastic modulus = 5.75 GPa, and tensile strength > 620 MPa). The fibers are commercially available and are made by a mix of polymers (mainly polypropylene). Due to the selected components reported in Table 1, TLC mixtures have a density of about 1650 kg/m^3.

With respect to these cement-based composites, new and more environmental-friendly lightweight concrete mixtures are tailored herein. Thus, the content of cement is reduced of about 30%, and rubber granulates substitute a portion of the aggregates. To maintain a density of the RLC lower than 2000 kg/m^3, an amount of 240 kg/m^3 of rubber is added to the new mixtures (see Table 2). Obviously, due to the higher water/cement ratio (twice than that of TLC) and to the presence of rubber, RLC will show a lower compressive strength, which in turn would not alter significantly the behavior of fiber-reinforced concrete beams and plates in bending [3]. As shown by Table 2, the new mixtures RLC_0, RLC_5, and

Table 1
Material components referred to 1 m^3 of traditional lightweight concrete TLC.

Components	TLC_0	TLC_7	TLC_10
Water (kg)	140	140	140
Cement Type II A-LL 42.5R (kg)	500	500	500
Stone aggregate (kg)	700	700	700
Expanded clay aggregate 3–8 mm (kg)	300	300	300
Superplasticizer (l)	5	5	5
Polypropylene fibers (kg)	0	7	10

Table 2
Material components referred to 1 m^3 of rubber lightweight concrete RLC.

Components	RLC_0	RLC_5	RLC_12
Water (kg)	168	168	168
Cement Type II A-LL 42.5R (kg)	352	352	352
Stone aggregate (kg)	1131	1123	1110
Rubber granulates 3–20 mm (kg)	243	241	238
Superplasticizer (l)	6	6	6
Polypropylene fibers (kg)	0	5	12