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Aggregates for innovative use in precast concrete panels: State of the Art and perspectives

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ABSTRACT: The use of lightweight and/or recycled aggregates for concrete elements in industrial applications for Civil and Industrial Engineering is strongly increased in recent years. Starting from classical use of pumice and other lightweight aggregates, the industry production of expanded clay and perlite offers interesting mix design that can optimize structural and energy performances of cladded panels. The authors illustrate recent experiences of research projects on the recycling of stone aggregates from demolition of r.c. structures in which mechanical properties are compared with natural aggregates. Several mix designs based on expanded perlite are also investigated in terms of mechanical and thermal performances optimizing both aspects: they are especially dedicated to full unit masonry walls and to create insulating-reinforcing panels to be coupled with masonry walls. Finally, is referred an experimental investigation with a concrete mix design of recycled aggregates, coming from collapsed buildings in central Italian area hit by earthquake 2016.

1 INTRODUCTION

This work presents the first result of an experimental campaign on the use of recycled aggregates in cladding panels. Cladding panels appears, in the context of precast concrete constructions, one of the most challenging elements for the application of recycled concrete. This because of the significant volume of material involved (on average 1/3 of the concrete of the whole concrete structure) and of the function of this elements (structural and thermal performances). Generally, from 70% to 80% of the volume of concrete is made up of natural aggregates.

It is estimated that 40% of the total energy and 50% of the total natural resources are used in construction activities. Nowadays, the construction sector is producing a significant amount of demolition waste and such waste constitutes the largest volume of all waste (Cheng et al., 2015). Construction and demolished wastes account for 25% to 30% of the whole waste that is being produced in Europe. The central part of Italy is prone to earthquake and has severely affected by earthquakes in the past 20 years (Rovida et al., 2016, Hofer et al., 2016). Post-disaster waste is an area of main concern and the debris can be recycled and used in the construction of new structures (Andreini et al, 2014) (Faleschini et al., 2017). Here the recycled waste obtained from the 2016 Earthquake in Italy will be employed for recycled concrete in the precast construction industry.

From this, the strategic relevance to use recycled aggregates in precast panels. In this work a mix design of concrete with fully recycled aggregates is proposed and studied aiming to compare the structural and thermal performances with respect to standard plain concrete currently used in production chain of Manini Prefabbricati.

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2 STATE OF THE ART

At the State of the Art the innovative use of concrete, using special aggregates or additive to obtain best structural and thermal performance and to have more sustainable production chain is a very significant challenge. The walls constitute the total weight of the structure, hence reducing the weight of the walls results in the reduced size of the foundation. The lightweight concrete panels also make it easy to move and mount these components in an easier way (Cavaleri et al., 2003). Precast concrete structures, with heavy self-weight, should be optimized for construction because they inevitably require heavier equipment, which makes transportation more challenging and necessitates the use of stronger bearing and support elements, especially considering the seismic action, and this could increase the overall cost of the project (Yardim et al., 2013).

Adopting lightweight concrete (LWC) reduces dead weight (Sajedi and Shafigh, 2012). Moreover, concrete with light-weight particles can have less thermal conductivity improving the energetic performance of the building. Typically, several Lightweight Aggregates (LWA) materials, including expanded glass (EG) aggregates, expanded clay (EC), pumice aggregate and plastic bottles, can be used to produce LWC. However, with these materials, the strength of the concrete generally decreases, so the application of these materials has its own limitations in terms of the mechanical response of the concrete (Adhikary et al., 2020). Several attempts are made to make LWC using some natural and artificial lightweight materials including shale, pumice, expanded clay, glass, etc., (Divya Bhavana et al., 2017, Kurpinska and Kułak, 2019, Singh, 2016).

The use of the steel fibres and the LWC based on the fly ash aggregates were investigated and it was found that these fly ash lightweight aggregates can produce some concrete with a compressive strength of 40 MPa (Longarini et al., 2014). The addition of the steel fibers in the lightweight aggregate concrete will increase the compressive strength and the tensile strength of the LWC (Güneyisi et al., 2015). (Mboya et al., 2019) investigated the effects of the scoria and pumice on the performance response of the concrete. They found that natural scoria and pumice binders can be substituted up to 10% without compromising the mechanical properties including permeability, modulus of rupture and the compressive strength of the concrete .

It is found that by using volcanic pumice, a concrete that is 30 to 40% lighter than typical concrete and has good insulation and structural strength properties can be produced (Campione et al., 2001, Hossain, 1999). Khankhaje, et al. used oil palm kernel shell (OPKS) as a partial replacement of the coarse aggregate in concrete mixes and concluded that OPKS amount had adverse effects on the mechanical properties of the concrete. The shape of the OPKS particles was round that disturbing the micro arrangements of the concrete resulting in inferior mechanical properties including the strength of the concrete (Khankhaje et al., 2016). This is just an example of construction materials based on bio natural aggregates. (Sassu et al., 2016) used the bio natural aggregate i.e., hemp shives and cork granules in concrete and recommended such material for non-load bearing structural components or combined with other structural elements. The experimental study evaluated the effects of these materials on the flexural and compressive response of concrete and found that the cork granules showed better mechanical performance. Such materials are recommended to use in insulating wall panels.

University of Cagliari has been starting work about production, performance and durability of recycled aggregates and recycled aggregate concretes since 2009. The most recent research project, "Materials for Sustainable Building and Infrastructure - Recycled Aggregates" (MEISAR), funded by Regione Sardegna, has aimed at developing an eco-sustainable chain of concrete constructions by enhancing recycled aggregates (Pani, L. et al., 2019, Pani, L. et al., 2021). The study featured several applications, including the substitution of recycled aggregates (instead of natural aggregates) in reinforced concrete. Seven different concrete mixtures were casted: one mix control made with only natural aggregates, and six mix made with recycled coarse aggregates from the demolition and crushing of the concrete structures (beams and foundation blocks) of the Sant'Elia Stadium in Cagliari. The samples are differentiated by the origin of the recycled aggregates and by the different percentages of replacement of the recycled coarse aggregate (introduced in place of natural aggregate). A production of compounds made with 30%, 50% and 80% recycled coarse aggregates instead of natural ones, was provided. In this case, no substantial differences in compressive and in splitting tensile strengths between the different

mixtures have been observed. In fact, in some cases the recycled concrete samples showed slightly higher strengths with respect to the natural mix control samples (Pani, L. et al., 2020).

Additional tests were also carried out on blocks with recycled aggregates obtaining quite similar results and slightly lower compressive strength at 70% replacement rate and an almost unchanged strength for lower replacement rates. Further tests performed on structural elements such as plinths and columns at life (or at a smaller scale) showed similarly encouraging results. (Pani, L. et al., 2022).

The history of structural concrete highlights a non-negligible problem: the significance of mixing process (segregation of aggregates) and effectiveness of the casting that can produce a variable mechanical behaviour of concrete and so in the structural response. (Puppio et al., 2017, Puppio et al., 2019) investigated the impact of the material variability on global and local seismic response of the structure. (Crespi et al., 2022, Puppio et al., 2017) also proposed a simplified method to consider the material irregularity while performing the seismic assessment. The mechanical properties of the concrete i.e., effective compressive strength greatly affects the response of the structural elements in case of seismic activity. Three material strengths were considered during the study to check the global response and seismic performance (De Stefano et al., 2020).

The use of recycled aggregate has become an alternative material to the natural aggregate in construction industry worldwide. It will directly control the accumulation of the waste along with saving the natural resources (Noguchi et al., 2015, Quattrone et al., 2014, Fauzi et al., 2021). (Attri et al., 2021) used the recycled aggregates to prepare concrete paver blocks and found that the 45 % of the coarse aggregate and 40% fine aggregate can be replaced without compromising the strength of the structural elements (Ruslan et al., 2021) replaced the natural aggregates with recycled aggregates in the precast wall panels mix. The researcher found that by replacing the 50 % natural aggregate can enhance the effectiveness of the wall panels by 179.5% compared with the wall panels prepared with the natural aggregates only. Moreover, using the wall panels with 50 % recycled aggregate can have 203.26 kN higher ultimate load capacity compared with the wall panels with 0 % and 100 % natural aggregate samples.

As discussed, lightweight or recycled aggregates represent an interesting application in the building of cladding panels. Recycled aggregates from Assisi'2016 earthquake is a 0km-resource for the Manini's production in Bastia Umbra, but it also has a high symbolic value for what the Assisi Earthquake represented for Umbria and for Italy. For all the explained reason the strategic role of this experimental campaign.

3 METHOD

The standard production of precast prototypes is based on a proprietary concrete mix that optimizes the available natural resources and the mixture processing. The mix design *B* (mdB) is used by Manini for the construction of ordinary structural member, and it represents the base mix for the integration of the recycled aggregates (mix design *A* - mdA). The only difference between mdB and mdA is in the coarse aggregates: natural in the first case and recycled in the second case.

The mix designs are both based on the same concrete quantity and water to concrete ratio and an experimental structural and thermal characterization has been achieved according to the following European Standards:

– Shape, dimensions and other requirements for specimens and moulds: UNI EN 12390-1 (Table 1).

Table 1. Specimens.

Tests	Dimensions [mm]			n.
Compression - mdA	150	150	150	5
Tension - mdA	150	150	150	5
Elastic modulus - mdA	cylinders ϕ=150		300	3
Thermal conductivity - mdA	100	100	50	10
Thermal conductivity - mdB	100	100	50	10

– Making and curing specimens for strength tests: UNI EN 12390-2.
– Uniaxial compression tests: UNI EN 12390-3 (5 specimens).
– Indirect tension tests: UNI EN 12390-6 (5 specimens).
– Secant modulus of elasticity in compression: UNI EN 12390-13 (3 specimens).
– Thermal conductivity: UNI EN 12664 (10 specimens for each mix design) (Table 1).

4 EXPERIMENTAL CAMPAIGN

4.1 *Test set up*

Uniaxial compression tests and tensile splitting tests are carried out by applying an increasing force until the specimen's failure. The uniaxial compression tests are carried out, according with UNI EN 12390-3, applying a quasi-static force throughout rigid steel plates. Tensile strength is determined according to the recommendations of UNI EN 12390-6, through the application on the cubic specimen of a linearly distributed load on a narrow region along its length. In this case failure is obtained due to orthogonal tensile stress generated in the diametral plane. The modulus of elasticity is measured under compression on cylindrical specimens, according to UNI EN 12390-13 (Method B). The test is based on three stress cycles. Load application starting from a non-zero-base stress to the upper stress; every loading condition is maintained for a period not exceeding 20 seconds, following which the strain is recorded by means of a couple of electrical strain gauges 50mm length glued on each of two diametral opposite measurement lines. The stabilized secant modulus of elasticity $E_{C,S}$ is defined as:

$$E_{C,S} = \frac{\Delta\sigma}{\Delta\varepsilon_S} = \frac{\sigma_a^m - \sigma_b^m}{\varepsilon_{a,3} - \varepsilon_{b,2}} \tag{1}$$

where:

$\Delta\sigma$ Difference between measured upper and lower compression stress.
$\Delta\varepsilon_S$ Difference between average strain at upper stress on loading cycle 3 and at lower stress on loading cycle 2.

The test machines used for the experimental campaign above are illustrated in Figures 1 and 2.



Figure 1. Testing machine for compression tests on cubical specimens (a); testing machine for splitting tensile tests on cubical specimens and for modulus of elasticity in compression on cylinder specimens (b).

Thermal conductivity tests are performed by means a heat flow meter measuring device, model Taurus TCA300, at three different mean specimen temperature: 10 °C; 20 °C; 30 °C. The thermal flow is generated by a temperature gradient (ΔT) of 20 K between the heating and the cooling plates. The thermal flow Q propagating in the unit time on the surface of section A in the thickness direction, is connected to the conductive properties of the material and to the other measured quantities by the:

$$\dot{Q} = \frac{\lambda \cdot \mathrm{A} \cdot \Delta\mathrm{T}}{\mathrm{s}} \tag{2}$$

Thermal conductivity λ is calculated from Equation 2, known the thermal flow Q. The device Taurus TCA300 is in Figure 2 while the scheme for the thermal conductivity test is showed in Figure 3.



Figure 2. Thermal conductivity measuring device, model Taurus TCA 300.

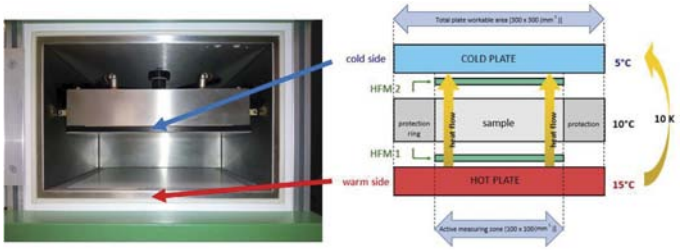


Figure 3. Inside view of the heat flux measuring device and scheme for the thermal conductivity test at the temperature of 10°C.

4.2 *Tests*

Tests are performed at the Material Testing Laboratory and at the Technical Physics Laboratory of the Department of Civil, Environmental Engineering and Architecture (DICAAR) of the University of Cagliari.

Both mechanical and thermal stress are carried out after a 28-day curing period. The specimens are classified by means of progressive numbers, NP*xxx* as Figure 4 shows. Dimensions, weight, and density are resumed in Table 2. In the case of specimens for thermal tests, the specimens with recycled aggregates are labelled by the letter *A* while the plain concrete by Manini is identified by the letter *B*. The labels of the specimens are showed in Figure 3.

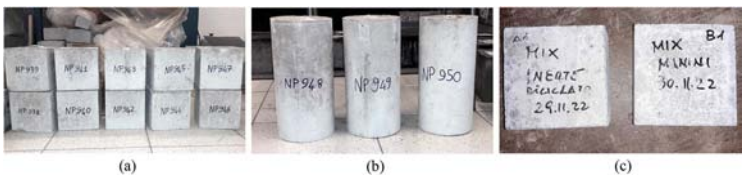


Figure 4. Labels of the specimens: cubic specimens for uniaxial compression and indirect tension tests (a); cylindrical specimens for the elastic modulus (b); two samples of specimens for thermal tests (c).

Mechanical tests carried out by Manini Prefabbricati on the original mix design (after 28 days of aging) highlight the following average values:

- Density 2387 kg/m^3;
- Cubic compressive strength 48.4 N/mm^2;

Figure 4 shows some pictures of the tests already performed.



Figure 5. Mechanical tests: uniaxial compression test (a); splitting tensile test (b); determination of secant modulus of elasticity in compression and uniaxial compression test (c).

The specimens tested for thermal conductivity were previously milled to regularize their faces from any surface roughness. The thermal conductivity test has been carried out according to the following procedure: the specimen is equipped by a sheep wool side heat guard to generate a one-dimensional heat flow through the transverse direction of *s* width and then placed within the heat flow meter measuring device between the heating and the cooling plate. Each individual established temperature range value is maintained for 180 minutes, while the average parameters are acquired and updated every 3 minutes; each test takes approximately 9 hours.

4.3 *Results*

Main geometry of the specimens for mechanical testing is summarized in Table 2. Data obtained from tests are:

- Density 2239 kg/m^3;
- Cubic compressive strength 47.0 N/mm^2;
- Splitting tensile strength 3.0 N/mm^2;
- secant modulus of elasticity gives the values of 32.7 GPa.

Main results of the thermal conductivity tests are summarized in Figure 6. The average thermal conductivity is:

- 0,493 ± 0,04 W/mK for the concrete with recycled aggregates (mdA).
- 0,502 ± 0,05 W/mK for plain concrete (mdB).

Table 2. Main data of the specimens with recycled aggregates.

P.N.	Dimensions [mm]			Density D [kg/m^3]
938	149	150	149	2270.2
939	152	150	151	2175.6
943	148	149	149	2233.9
950	148		300	2276.7
940	150	150	150	2269.6
941	151	149	149	2240.2
942	151	150	149	2254.9

5 CONCLUSIONS

The thermal conductivity of the specimens obtained by recycled concrete does not changes significatively. The compression strength of recycled concrete specimens seems to be satisfactory for structural uses (mean value of 47 MPa) showing the (97% of the strength of the original mix design). The density of the specimens is 2239 kg/m^3 (94% of the density of the original

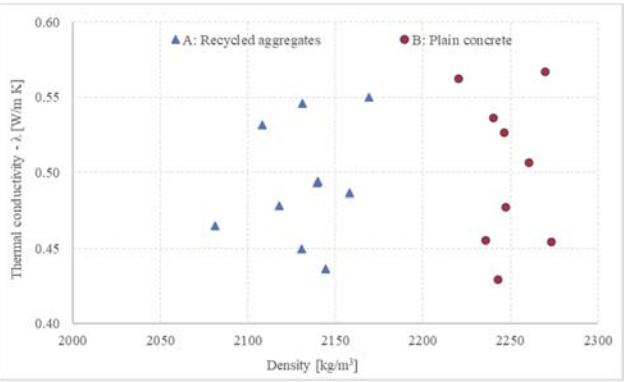


Figure 6. Determination of thermal conductivity for specimens with recycled aggregates (mdA), and with plain concrete by Manini (mdB).

mix design). The experimental campaign should be enforced to ensure statistical significance of the results, anyway the first data are encouraging. In this perspective, the use of recycled aggregates on concrete structures can ensure the following advantages:

1. Recycled aggregates obtained by demolition of damaged buildings from seismic prone areas reduces the environmental and economic impact of the reconstruction phases.
2. Satisfactory compression strength permits the structural use for panels or other precast elements.
3. The use of recycled aggregates on precast elements reduced the critical issue of ensuring quality control, respect to onsite casting elements: the uncertainness of recycled elements can be better managed in precast element layout respect to onsite works.

Further tests at the scale of material should be arranged to best investigate the above performances as well as the material compatibility with tradition reinforcing bars. Moreover, tests at the element scale (panels, beams, columns) can better assess the feasibility of the described idea.

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