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"USE OF RECYCLED AGGREGATES IN ROAD SUB-BASE CONSTRUCTION AND CONCRETE MANUFACTURING"

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ABSTRACT

This paper investigates the use of construction and demolition waste in road embankment and concrete manufacturing. The aggregates are recycled from the demolition waste of a building and in particular from basalt, sandstone, structural concrete and vibrated concrete blocks. The main physical characteristics of recycled aggregates for road applications and the performance of road sub-base layers containing recycled components are determined and validated on the basis of the latest Italian specifications. The study demonstrates that recycled mixes have sufficient mechanical characteristics and are hence suitable in road sub-base construction, even if only limited to minor technical importance works. Moreover, the mechanical properties of concrete mixtures that use recycled aggregates as replacement for natural aggregates are evaluated and compared to those of standard concrete mixtures. Three types of recycled aggregates are considered (structural concrete, basalt, vibrated concrete blocks) at different replacement ratios. A higher percentage of recycled aggregates than the one prescribed by the current legislations can be effectively used in concrete preparation, especially in the case of aggregates derived from crushed basalt waste or from structural concrete manufactured using basaltic fine and coarse aggregates. The effect of natural fine aggregate replacement with recycled fine fractions on concrete is investigated. The results of the experimental program are significant and encourage the use of 100% recycled basalt aggregate in concrete. Therefore, in areas where the use of basalt stone as primary masonry building material is widespread, the reuse of demolition waste is highly recommended.

1. INTRODUCTION

A large part of waste, the so-called Construction and Demolition (C&D) waste, originates both from new construction and demolition of existing constructions. Waste deriving from the ruins produced by catastrophic natural disasters, such as earthquakes and floods, often adds to C&D waste.

C&D waste is heterogeneous in its composition because it includes concrete, natural stone, glass and many kinds of ceramic materials, metals, wood, rubber, gypsum, bituminous parts and so on. Many of these components can be differently recycled. In the case of demolition of reinforced concrete structures, the amount of structural concrete waste is obviously predominant. In the last decades, sustainability and in particular waste management and recycling has become a priority. Re-use of C&D waste in construction industry prevents overloading of landfills and the exploitation of natural resources. Recycled aggregates are generally used as partial or total replacement of natural aggregates, both in concrete and in mortar, two widely used building materials. Moreover, recycled aggregates deriving from C&D waste are used in road embankment manufacture. A large number of scientific publication exists on the topic. Nowadays, research on pavement construction focuses in the identification of optimal blends of recycled materials that may be used as unbound granular materials. The reuse of C&D waste containing concrete waste and recycled masonry brick materials is studied in [Poon and Chan, 2006; Vegas et al., 2011; Barbudo et al., 2012; Arisha et al., 2016]. The environmental performance of recycled mixed C&D waste for road and railway embankments in terms of leachate is investigated in [Cristelo et al., 2016; Roque et al., 2016], while the recycling of asphalt road waste is studied in [Behnood et al., 2015]. An extensive review of recent research work on the use of geosynthetics for the stabilization of recycled aggregates containing concrete, asphalt pavements, and ballast in roadway construction can be found in [Hana and Thakurb, 2014]. The preparation of asphalt base from recycled concrete aggregates, treated at different levels with activators such as organic silicon resin, metatitanic resin and silane resin acceptors is studied in [Hou et al., 2014]. Unusual aggregates, such as shredded tyre rubber and grinded polypropylene bottles are proposed in [Krishnamoorthy et al., 2016] for the replacement of coarse and fine aggregates in concrete mixtures used in road construction. The possibility of applying recycled concrete aggregates in road bases as Cement Treated Granular Material (CTGM) for the improvement of their mechanical performance and durability is investigated in [Pérez et al., 2013]. Recycled concrete aggregates may be also used in bituminous mixtures [Pasandín and Pérez, 2015]; suggestions for the preparation of cement bound mixtures can be found in [Pasetto and Baldo, 2016]. In their majority, the studies cited above aim to verify that the recycled products satisfy the requirements of the existing standards in the country of reference, i.e. Brazil, Spain, Egypt, China.

Regarding the application in concrete manufacture, a comprehensive review of the most important publications on the effects of recycled aggregates on the material performance of concrete over the last forty years can be found in Silva et al. in [Silva et al., 2014, 2016]. The use of recycled aggregates derived from precast wastes [Thomas et al., 2016; de Brito et al., 2016] or commercially produced [Sagoe-Crentsil et al., 2001] has also been studied.

The Italian standard NTC2008 (Norme Tecniche per le Costruzioni 2008) limits the use of coarse recycled aggregate in construction for structural purpose to 30%, while a miscellany of recycled aggregates is admitted for low strength concrete. In fact, the rubble usually consists in a mix of various construction and finishing materials, whose mechanical properties cannot be univocally fixed [Rao et al., 2007]. Further regulations prescribe the usage of C&D waste in road construction and environmental works.

Nevertheless, a wide selection of studies focuses on the use of fine recycled aggregates for structural purpose [Khatib, 2005; Evangelista and de Brito, 2007; Cabral et al., 2010; Fan et al., 2016]. Alternatively, fine recycled aggregate can be used in mortar manufacturing. The influence of the fine recycled fraction on the physical and mechanical properties of recycled aggregate mortar, both of fresh and hardened paste, is discussed in [Westerholm et al., 2008; Corinaldesi and Moriconi, 2009a; Corinaldesi et al., 2011; Jiménez et al., 2013; Neno et al., 2014; Zhao et al., 2015]. The factors that should be taken into account when we experimentally evaluate the properties of recycled aggregate concrete are highlighted in [Silva et al., 2014; Vegas et al., 2015; Al-Bayati et al., 2016; Tam et al., 2005, 2007; Laserna and Montero, 2016; Xiao et al., 2006; de Brito et al., 2016; Omary et al., 2016; Zhang et al., 2008]. Finally, a review on the use of recycled aggregates in geotechnical applications can be found in [Cardoso et al., 2016]. To the author's knowledge, few studies present experimental results concerning concrete with recycled basalt aggregates. The effect of four different types of natural coarse aggregates (granitic, basaltic, quartzitic crushed stones and a siliceous gravel), of different shape, composition and surface texture, on the physical and mechanical properties of recycled coarse aggregates obtained by crushing four conventional concretes with different water/binder ratio is examined in [Zega et al., 2010]. The possibility of using recycled Mt. Etna volcanic pyroclasts for cement, mortar and concrete manufacturing is investigated in [Contrafatto, 2017]. Ajdukiewicz and Kliszczewicz [2002] report the results from a study on the properties of High Performance Concrete, obtained using recycled aggregates from moderate-or high-strength concrete with original granite or basalt aggregates. The recycled aggregates were taken from six demolished concrete structures, five made with crushed granite coarse aggregate and one with basalt. The results show that it is possible to obtain recycled aggregate concrete with higher compressive strength than the original one. However, the study focuses on concrete with recycled concrete aggregates containing originally natural basalt aggregates and not recycled basalt aggregates.

A distinct branch of the literature is devoted to the study of the constitutive response of concrete with recycled aggregate by means of numerical predictions. For instance plastic-hardening-damage-fracture Finite Elements numerical models [Contrafatto and Cuomo, 2006, 2007; Contrafatto and Ventura, 2004] and homogenization techniques at meso-scale level accounting for the damaging behavior of the components [Contrafatto et al., 2016; 2017] are used. Internal friction phenomena [Scerrato et al., 2016b], occurring due to microparticle addition [Scerrato et al., 2016a] can be also considered. Other numerical tools, based on elements with embedded discontinuities [Contrafatto et al., 2012] may also be implemented.

The Italian territory is characterized by a rich geological configuration; different types of soils and consequently different resources and construction materials can be found in different regions of the country. In East Sicily, the typical aggregate for production of conglomerate to be used for structural and non-structural purposes is Etna basalt, a basalt stone extracted from Mt. Etna volcano. The abundance of basalt stone in the region in square or irregular blocks shapes makes it the most popular material for building, boundary walls, retaining walls, road pavements and architectural components. As a consequence, a huge amount of the waste produced by the demolition of typical construction in the area contains Etna rock. The present research aims to investigate the reuse of C&D waste in road sub-base layers and in concrete manufacturing, even in the case that such materials do not comply with the existing Italian regulations. An extensive experimental program was carried out at the L & R Laboratories and Research. The first set of tests was developed ad hoc for the validation of the properties of recycled aggregates and unbound granular blends used in road sub-base construction. The second set of tests was designed for the understanding of the behavior of structural concrete with recycled aggregates in partial and total substitution of coarse and fine natural aggregates. The effect of recycled concrete and basalt coarse gravel and recycled sand obtained from vibrated concrete blocks was studied.

The paper is organized as follows. Section 1 is introductory and presents the problem at hand and the motivation of the research. Section 2 focuses on the characterization of the recycled materials in consideration. Section 3 presents the tests performed on the recycled aggregate mixes prepared for road sub-base applications. Section 4 provides information on the experimental setting and the methodology adopted for the evaluation of recycled aggregate concrete and discusses the obtained results. The paper is concluded with a summary of the most significant findings.

2. RECYCLED MATERIALS

The materials were selected from the demolition waste of an ordinary building in the Sicily territory. The typical components of the waste were: structural concrete, plain concrete, vibrated concrete blocks, ceramics and in particular hollow and solid clay bricks, basalt, sandstone and glass. Only three class of waste materials were selected for the mix design of concrete with recycled aggregates, on the basis of their intrinsic mechanical properties and their suitability for structural concrete admixture, while two class of materials were selected in the case of road sub-base applications.

Uniaxial compression tests were performed on core samples extracted by monolithic blocks of different materials obtained from the demolition waste, to determine their suitability for concrete productions (Basalt σ_c = 41 MPa, Concrete σ_c = 29 MPa, Sandstone σ_c =1.9 MPa). There is a great variability in the individual σ_c values (the value depending on the single piece of debris and on the origin of the rocks [Pappalardo et al., 2013], that is however justified by the random characteristics of the recycled materials derived from debris. Contrary to sandstone, basaltic and concrete wastes are characterized by high compressive strengths and may be therefore used for the production of high quality recycled concrete. Sandstone was chosen for road sub-base applications. Moreover, vibrated concrete blocks were chosen to produce fine recycled aggregates. Clay bricks were discarded because the use of recycled brick aggregates in the finer section of the coarse recycled aggregates is effective, but their influence on the overall mechanical behavior of concrete is not univocal [Khatib, 2005; Cachim, 2010], strongly depending on the nature of the bricks. Furthermore, the study of the clay source material is beyond the scope of the present paper.

A natural aggregate (A) from a crushing plant located in Motta S. Anastasia, Catania, Italy, was considered for the preparation of the concrete mixtures. (A) was derived from basalt lava, in fine and coarse grain size, a common practice in the region. The basalt recycled aggregate (B) was obtained by crushing monolithic stones used in the construction of the building. The recycled concrete aggregate (C) was obtained from the debris of foundation reinforced concrete structures, originally produced using basalt fine and coarse aggregates. The vibrated concrete blocks aggregate (D) was made of Portland cement, basalt sand and gravel, characterized by maximum diameter size of 10 mm, and water. (D) was used both in the design of concrete mixes and in the case of road sub-base mixes. Sandstone recycled aggregate (S) was obtained by crushing monolithic stones and used only for the preparation of road sub-base mixes.

The crushing process of the debris involved several steps. The first, following the manual selection and cleaning of the materials in the demolition site, was performed in a recycling plant, located in a small city on the slopes of Mt. Etna, using a jaw crusher that may

FIGURE 1. (a) Recycled basalt aggregate (B). (b) Recycled structural concrete aggregate (C). (c) Recycled vibrated concrete blocks aggregate (D).

Material	Diameter range (mm)	Denomination
A1	0-4	natural basalt sand
A2	5.6-16	fine/medium natural basalt gravel
A3	16-31.5	coarse natural basalt gravel
A4	4-5.6	corrective sand
B1	5.6-11.2	fine/medium recycled basalt
B2	11.2-31.5	coarse recycled basalt

TABLE 1. Natural and recycled basalt aggregates sub-nomenclature.

produce particle sizes less than 50 mm. The successive steps were performed at the L&R Laboratories and Research s.r.l. in Catenanuova (EN), where successively the experimental tests were conducted, to obtain a more assorted size distribution.

The rough materials used in the preparation of recycled aggregate concrete, after the preliminary crushing, are shown in Figure 1.

It should be pointed out that a modest amount of adhered cement mortar on the recycled basalt aggregate was present, due to the typology of the construction technique. Therefore, a detailed study on the mortar content of the recycled aggregate could be purposeful

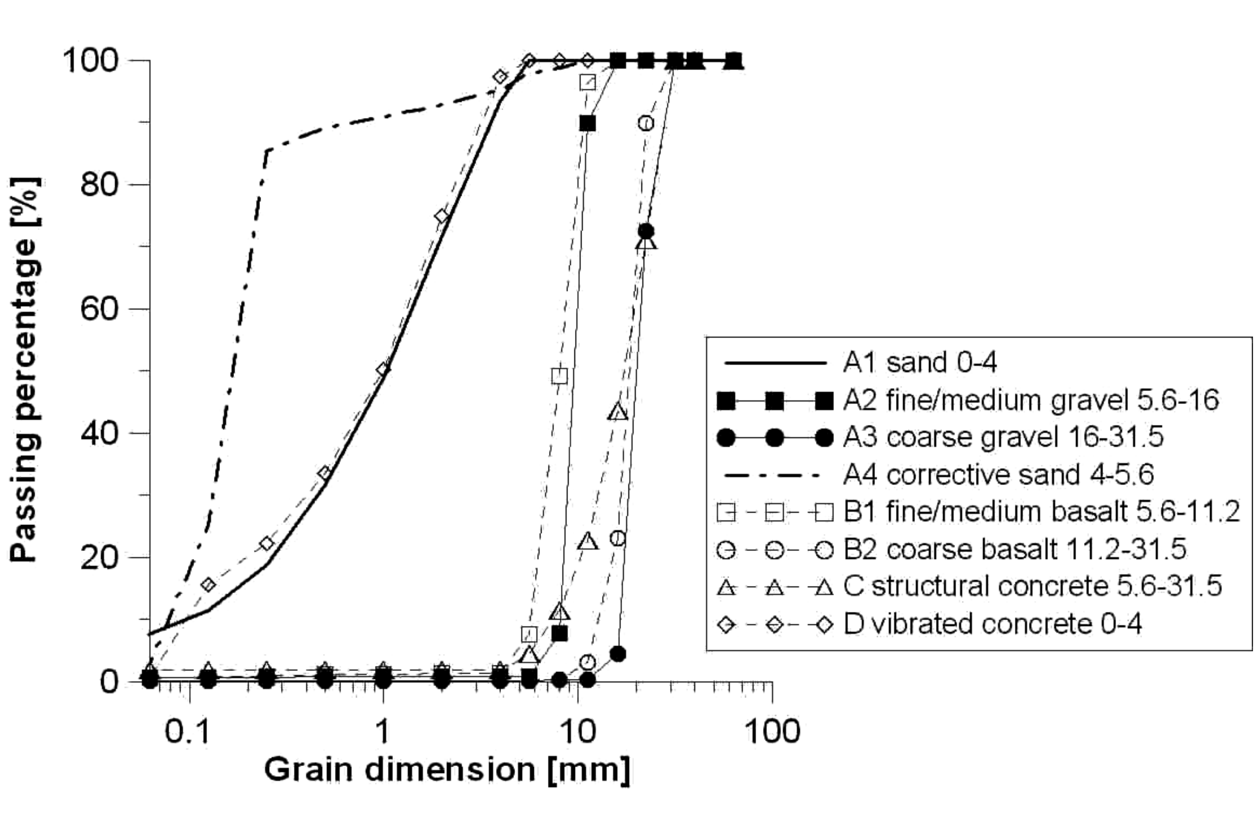

FIGURE 2. Particle size distribution curve.

Material	Diameter range (mm)	Volumetric mass density ρ_{aggr} (kg/m^3)	Water absorption coefficient (%)
A1	0-4	2758	1.90
A2	5.6-16	2768	1.84
A3	16-31.5	2734	1.60
A4	4-5.6	2591	1.96
B1	5.6-11.2	2602	3.04
B2	11.2-31.5	2702	2.85
C	5.6-31.5	2406	5.46
D	0-4	2632	3.58

TABLE 2. Aggregates volumetric mass density and water absorption coefficient

[Sánchez de Juan and Gutiérrez, 2009]. Following Wentworth grain size classification, both the natural and recycled basalt gravel were divided in coarse and fine/medium gravels. The sub-nomenclature presented in Table 1 was introduced, where the material labeled as A4 is a natural corrective basalt sand, used to adjust the mixtures according to the Bolomey curve.

In order to obtain the particle size distribution of both the natural and the recycled aggregates a sieve analysis was performed using a Tecnotest electric sieve shaker with timer SS207/B09. Figure 2 shows the particle size distribution curve for the natural and the recycled aggregates. Moreover, the volumetric mass density Maggr and the water absorption coefficient of the aggregates were experimentally determined. The results, reported in Table 2, show that the recycled aggregates exhibit higher water absorption compared to natural aggregates, the highest value corresponding to recycled concrete. As confirmed by other authors, among them [Eguchi et al., 2007; Gomes and de Brito, 2009; Zega et al., 2010], the higher the water absorption, the lower the mass density. The higher water absorption of the coarse recycled concrete aggregates can be ascribed to the presence of the old cement mortar attached to the aggregate particles [Hansen and Marga, 1988].

For road sub-base mix preparation only sandstone recycled aggregates (S) and vibrated concrete blocks aggregates (D) were considered. The materials from C&D waste are extremely heterogeneous; in order to evaluate their suitability for such application, they were classified into three categories:

- Not bound recycled products;
- Bound recycled products with hydraulic binder (cement, lime) or bituminous binder (bitumen, bitumen emulsion);
- Products for stabilization works in situ.

In this work the selected materials were considered as “Not bound recycled products” and the possibility of using them in a mix for road sub-base was evaluated as in section 3. In this study, the national regulations, and in particular the Technical Specifications of the Authority for the road public network ANAS (Azienda Nazionale Autonoma delle Strade), were used as reference for the validation of recycled stone aggregates for road sub-base applications.

The results obtained from the testing of crushed materials are shown in Table 3, where reference is made to the current legislation.

Both recycled materials have properties well within

Test	Standard	Range	D	S
Sand equivalent (%)	UNI EN 933-8 ANAS Tech. Spec.	> 30 40 < x < 80	68	31
Los Angeles (%)	UNI EN 1097-2 ANAS Tech. Spec.	≤ 45 40 < x < 80	56	74
Fine content (%)	UNI EN 933-1	≤ 15	1.3	1
Shape index (%)	UNI EN 933-4	< 40	16	10
Flattening index (%)	UNI EN 933-3	< 35	14	9
Proctor Compaction	UNI EN 13286-47	Maximum density (g/cm^3) Optimum moisture (%)	2.065 8.9	2.101 8.2
CBR (%) CBR (after 96 h) (%)	UNI EN 13286-47 ANAS Tech. Spec.	> 30 > 350	99	77

TABLE 3. Recycled materials characterization tests and acceptance limits.

the limits prescribed by the existing regulations, with the exception of the Los Angeles resistance to fragmentation and the sand equivalent value. In fact, both materials show higher resistance at fragmentation than the one required by the corresponding specifications.

3. ROAD SUB-BASE MIXTURES AND EXPERIMENTAL TESTS

The results of the tests on aggregates (D) and (S) were not entirely satisfactory. However, further experiments were performed in order to evaluate the performance of the materials obtained after mixing the two basic materials (D) and (S), and establish the optimal mixing ratios. Three mixes were prepared, namely mixes R_1, R_2 and R_3, see Table 4. The test results, with reference to the ANAS Technical Specifications, are given in Table 4.

The experimental results show that the particle size distribution curve is continuous and gradual and almost identical to the lower limit of the ANAS reference grading envelope (mixes R_1 and R_2). In the case of mix R_3, this curve is slightly different than the reference one; the gradual trend is less obvious compared to mixes R_1 and R_2 due to the lower presence of particles of size 16 to 19 mm and the higher concentration of particles with size within 6.3 and 9.5 mm. However, from a practical point of view the performance of mix R_3 is acceptable.

The remaining tests were used for the verification of the required prescriptions. In particular:

- all the mixes, owing to the crushing procedure of the original materials, contain a sufficient quantity of small particles that ensures the binding effect during the compaction phase;
- all the mixes show good behavior under compaction; the values of the maximum density of the dry material and the optimal moisture are in line with the ones reported in literature for calcarenitic/sandstone quarry materials;
- the CBR values for mixes R_1, R_2 and R_3 after 96 hours of imbibition in water lie in the range 69-76%, and are always greater than the ones prescribed by ANAS (50%), confirming the good performance of the materials to compaction, lift and their low susceptibility to water.

It is important to note that the particle size distribution curves of the examined mixes, and in particular mix R_3, can be improved through the addition of a low percentage of a natural sand of suitable grain size. In such case the distribution curve of the mix is contained within the reference grading envelope prescribed by ANAS.

Test	ANAS Tech. Spec.	Mix R_1 25% D + 75% S	Mix R_2 50% D + 50% S	Mix R_3 75% D + 25% S
Max diameter (mm)	< 63	< 63	< 63	< 63
Particle size analysis	Fine particles (%) Prescribed grading envelope	1.2 Verified	2.8 Verified	1.2 Slightly not verified
Modified Proctor compaction	Maximum density (g/cm^3) Optimum moisture (%)	1.984 9.5	2.047 8.8	1.929 9.4
CBR (after 96 h) (%)	> 50	69	74	76
Sand equivalent (%)	> 40	43	54	63

TABLE 4. Recycled road sub-base mix characterization tests and acceptance limits.

4. CONCRETE MIXTURES AND EXPERIMENTAL TESTS

The experimental campaign was developed for the determination of the physical and mechanical properties of concrete obtained using in the mixture the three selected recycled materials. The main research objectives were the investigation of the influence of the complete substitution of coarse aggregates with recycled basalt coarse gravels on concrete strength and the assessment of the possible re-use of these recycled aggregates for structural concrete applications, as in the case of recycled concrete aggregate. Moreover, the effect of the partial substitution of fine natural aggregates

Mixture	Fine aggregate $0 \leq d \leq 4$ mm		Coarse aggregate $5.6 \leq d \leq 31.5$ mm	
	quarry	demolition	quarry	demolition
	(%)	(%)	(%)	(%)
$M_{0\text{-}0}$	100	0	100	0
$M_{0\text{-}30C}$	100	0	70	30C
$M_{0\text{-}50C}$	100	0	50	50C
$M_{0\text{-}70C}$	100	0	30	70C
$M_{0\text{-}100B}$	100	0	0	100B
$M_{77D\text{-}0}$	23	77D	100	0
$M_{77D\text{-}100B}$	23	77D	0	100B

TABLE 5. Prepared mixtures, characterized by different ratios of natural and recycled aggregates.

with recycled sand derived from vibrated concrete blocks was investigated.

4.1 CONCRETE MIXTURES

For the preparation of all the concrete specimens a commercial Portland cement, type CEM II/B-LL 32.5R by Italcementi S.p.A., according to European Norm EN-197-1, was used. One reference concrete and six mixtures were designed, each one containing a partial substitution of the natural aggregate with recycled aggregate. All mixtures were defined by the characteristic compressive strength at 28 days R_{ck} = 30 MPa, identified by the strength class C25/30, according to standard EN 206. Coarse and fine aggregates were substituted in different percentage. Table 5 provides the characteristics of the designed mixtures.

The mix design was performed arranging both the coarse and fine aggregates fractions following the Bolomey optimal grain size distribution of solid particles, described by the formula:

$$p_i = A + (100\,A)\left(\frac{d_i}{D_{max}}\right)^{0.5} \qquad (1)$$

where p_i is the percent passing the i^{th} sieve, d_i is the opening size of ith sieve, D_{max} is the maximum aggregate particle size and A is a parameter that takes into account the particle shape of the aggregate and the concrete consistency. A consistency class S_4 (fluid, 160-210 mm) of fresh concrete was fixed. The value A = 14 was chosen in formula (1), because the aggregates derives from a crushing process.

Figure 3 shows the comparison between the ideal Bolomey optimal curve and the real size distribution curves obtained from the laboratory testing of the mixtures. In addition to the consistency class S_4, a fixed water/cement ratio w/c was used in the design, according to EN 12350-2. The cement content was calculated in order to reach the compressive strength of 30 MPa at 28 days. For w/c =0.6, the cement content equals 359 kg/m^3. The fixed consistency was achieved, for a fixed water content of 220 kg/m^3, by introducing the BASF Construction Chemicals superplasticizer Glenium Sky 529 and by varying its content in the mixture. Owing to the presence of the superplasticizer (SP), a reduction of the order of 20% of the water content was achieved. The reduction of the water content from 220 to 176 kg/m^3 resulted to the reduction of the water/cement ratio from 0.60 to 0.49. The aggregates content was calculated from the balance between the total volume of the mixture V and the volume of water V_w, cement V_c, entrained air V_a and superplasticizer V_{SP}:

$$V_{aggr} = V - V_w - V_c - V_a - V_{SP} \qquad (2)$$

In formula (2) V = 1000 l/m^3, while V_a represents the volume in liters per m^3 of the entrained air, estimated equal to 20 l/m^3. The content of superplasticizer was calculated in percentage of weight of cement, depending on the nature of the aggregates, as specified in Table 6. The volume of aggregates was calculated from equation 2 by introducing the weights per unit volume of each component (water w_w =1.0 kg/l, cement w_c =3.15 kg/l, air w_a =0.00129 kg/l, SP w_{SP} =2.65 kg/l).

The resulting aggregates volume V_{aggr} is given by the sum of the gravel and sand contents V_g and V_s. The particle size analysis of gravel and sand in Figure 2 was used for the calculation of the gravel and sand quantities required to obtain the particle size distribution of reference with the minimum intergranular void. A maximum diameter size d = 31.5 mm was considered for the aggregates.

Table 6 provides the weights of the considered mixture components. For the mass density ρ_{aggr} given in Table 2, the content M_{aggr} in kg/m^3 of the aggregates was calculated as the product between the volume of the aggregates and the mean mass density:

$$M_{aggr} = \frac{V_{aggr}}{1000} \sum_i \rho_{aggr_i} \%_{aggr_i} \qquad (3)$$

$\%_{aggr_i}$ being the percentage of the i-th aggregate with respect to the total volume V_{aggr} of aggregate in the mixture that guarantees the optimal grading curve. The values are indicated in Table 6.

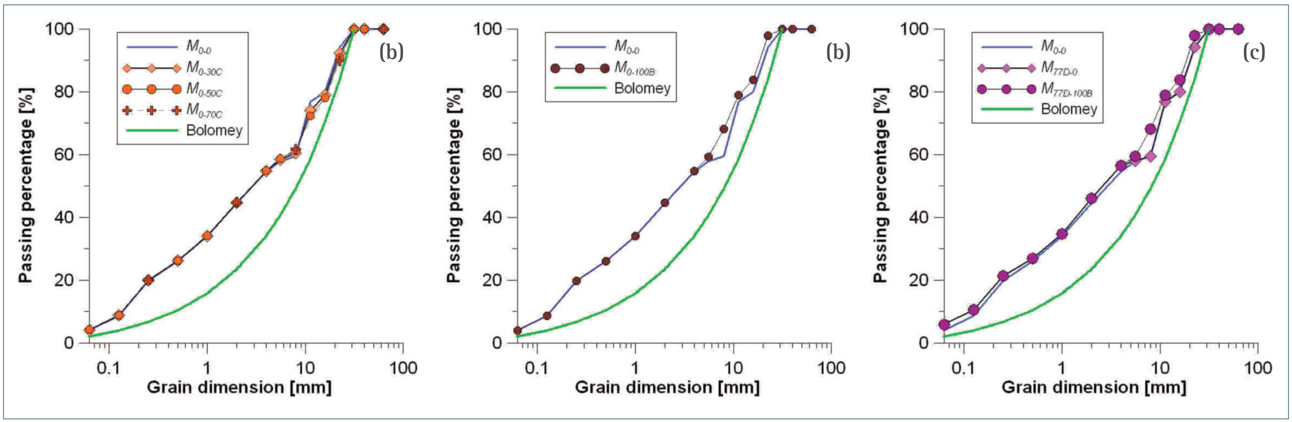

FIGURE 3. Comparison between the Bolomey optimal grain size distribution curve and the real grain size distribution in the mix design. (a) Mixtures $M_{0\text{-}0}$, $M_{0\text{-}30C}$, $M_{0\text{-}50C}$, $M_{0\text{-}70C}$; (b) Mixtures $M_{0\text{-}0}$, $M_{0\text{-}100B}$;(c) Mixtures $M_{0\text{-}0}$, $M_{77D\text{-}0}$, $M_{77D\text{-}100B}$.

4.2 EXPERIMENTAL TESTS

For each type of mixture 10 cubic specimens of side 150 mm, 3 prismatic samples 1500x150x600 mm^3 and 6 cylinders of diameter d = 150 mm and height h = 300 mm were prepared. At the same time, the tests for the determination of the properties of fresh concrete were carried out. The samples were removed from the molds after 24 hours and cured at a constant temperature of

Mixture	M_{0-0}	M_{0-30C}	M_{0-50C}	M_{0-70C}	M_{0-100B}	M_{77D-0}	$M_{77D-100B}$
SP (%)	1.1	0.9	0.9	0.9	1.0	1.0	1.0
SP (l/m^3)	3.95	3.2	3.20	3.20	3.60	3.60	3.60
V_{aggr} (l/m^3)	686.1	686.8	686.8	686.8	686.4	686.4	686.4
A1 (%)	45	45	45	45	45	-	-
A1 (kg/m^3)	814	831	822	813	831	-	-
A2 (%)	21	14.7	10.5	6.3	-	21	-
A2 (kg/m^3)	394	272	192	114	-	386	-
A3 (%)	21	14.7	10.5	6.3	-	21	-
A3 (kg/m^3)	394	272	192	114	-	386	-
A4 (%)	13	13	13	13	13	13	13
A4 (kg/m^3)	244	240	238	235	240	239	235
B1 (%)	-	-	-	-	21	-	21
B1 (kg/m^3)	-	-	-	-	388	-	380
B2 (%)	-	-	-	-	21	-	21
B2 (kg/m^3)	-	-	-	-	388	-	380
C (%)	-	12.6	21	29.4	-	-	-
C (kg/m^3)	-	233	384	531	-	-	-
D (%)	-	-	-	-	-	45	45
D (kg/m^3)	-	-	-	-	-	827	814
M_{aggr} (kg/m^3)	1875	1847	1828	1808	1848	1837	1809

TABLE 6. Content of superplasticizer and aggregates in the mixtures.

Fresh concrete	
Consistency	EN 12350-2 (2009)
Volumetric mass density	EN 12350-6 (2011)
Hardened concrete	
Density	EN 12390-7 (2009)
Compressive strength	EN 12390-3 (2011)
Flexural strength	EN 12390-5 (2009)
Splitting tensile strength	EN 12390-6 (2009)
Young's modulus	EN 12390-13 (2013)

TABLE 7. Tests on laboratory specimens.

22° C and humidity of 95% until strength testing.

The experimental campaign aimed to the determination of the physical and mechanical properties of concrete with recycled aggregates produced in laboratory conditions. The fresh and hardened concrete properties are shown in Table 7.

The mean compressive strength σ_c for ten cube specimens at 3,7,14 and 28 days of cure was measured using a LBG C287 system composed by a 3000 kN frame, combined with pressure transducer, data acquisition and remote management systems (see Figure 4). The mean tensile strength σ_t at 28 days of cure was obtained through splitting test of three cylinders. The mean flexural strength σ_f at 28 days of cure was obtained through three point bending test of three prismatic samples.

The mean value of the elasticity modulus was obtained from the testing of three cylinders. Three cyclic loading paths performed at three different stress steps $\sigma_1 = 1/9\sigma_c$, $\sigma_2 = 2/9\ \sigma_c$, $\sigma_3 = 3/9\sigma_c$, and starting from the base stress $\sigma_0 = 1/30\sigma_c$, were imposed using the 3000 kN compression testing machine Tecnotest system KD 300. Three CONTROLS inductive transducers, with adjustable gauge length varying from 50 to 160 mm, were connected to the automatic control console. The considered σ_c values are given in Table 9. The mean value of the secant modulus for each specimen was evaluated from the three measured stabilized moduli at the three different stress steps.

4.3 RESULTS AND DISCUSSION

4.3.1 Consistency

The slump test provided measures in the range 160-210 mm, for all mixtures considered, confirming the consistency class fluid S_4. Figure 4 shows mixture $M_{0\text{-}100B}$ during the slump test. Despite of the higher water absorption of recycled aggregates, the presence of the superplasticiszer, in the proportion given in Table 6, ensured the required workability.

FIGURE 4. (a) Concrete mix $M_{0\text{-}100B}$: Monotonic uniaxial test for the measure of the compressive strength σ_c. (b) $M_{0\text{-}100B}$ mixture -Slump test.

4.3.2. Fresh and hardened density

The evolution of the volumetric mass density with the age of cure is shown in Figure 5. Results indicate a reduction of density when recycled aggregates are used and confirm the typical trend with the age of cure. The reduction is more significant when the percentage of substitution of the natural aggregates is greater than 30%. However, it is always in the order of 4% (see Table 8). The maximum value of the coefficient of variation was found to be 11.3%.

Even though the six considered mixtures are characterized by comparable compressive strengths, mixture $M_{77D\text{-}100B}$ has the lowest volumetric mass density, see Figure 6. Since mixtures $M_{0\text{-}100B}$ and $M_{77D\text{-}100B}$ contain 100% coarse recycled basalt, they were expected to yield the same density. However, due to the aleatory morphology of the recycled basalt, the difference, not greater than 3%, is considered negligible.

4.3.3. Compressive, tensile and flexural strength

Table 9 and Figure 6 report the mean value of the compressive strength, measured on 10 specimens for each mixture at the different stages of hardening. The maximum value of the coefficient of variation was found to be 8.2%.

Table 9 reports the percentage decrement Δ of the compressive strength for the six mixtures containing recycled aggregates, with respect to the strength of the basic mixture $M_{0\text{-}0}$ at the same age of cure. A decrement in the compressive strength is observed and is in line with existing studies in the field.

As underlined by [Laserna and Montero, 2016] in the case of mixtures containing crushed natural aggregates, the shape of the aggregates may influence the strength properties. The main differences lie in the range [-31.4%,+16.0%] for the age of 3 days. Mixture $M_{0\text{-}30C}$ shows the best performance until the 14th day of cure, after which the strength reduces by 3% and becomes comparable to $M_{0\text{-}0}$. Mixtures $M_{0\text{-}50C}$, $M_{0\text{-}70C}$ and $M_{77D\text{-}0}$ exhibit a similar behavior, with a loss of strength in the range of 20-25%, that falls to 13-21% at the age of 28 days. An increasing fraction of recycled coarse aggregates, from 30% to 70%, introduces an increasing degradation of the mechanical strength, as it can be observed by comparison of the corresponding values for mixtures $M_{0\text{-}30C}$, $M_{0\text{-}50C}$ and $M_{0\text{-}70C}$ at 28 days. Furthermore, the substitution of the total amount of coarse aggregate with recycled basalt aggregate introduces a reduction in the order of 19% at 28 days (compare mixtures $M_{0\text{-}0}$ and $M_{0\text{-}100B}$).

These results are consistent with the literature and may be compared for instance to the ones reported in [Lovato et al., 2012] where a substitution of 100% of coarse aggregates translates to a 24% reduction in the concrete strength. In the experimental campaign reported in [Lovato et al., 2012], different kinds of concrete were produced, using recycled aggregates obtained from the grinding of C&D waste in the following proportions: 44.20% of mortar, 18.30% of concrete, 35.60% of red ceramics, 0.10% of white ceramics and just 1.80% of rocks.

These recycled aggregates have a poorer content of basaltic aggregates compared to the one used in the present research, giving rise to a higher degradation of the peak strength (24%) against 19.1%, 17.3% for mixtures $\mathrm{M}_{0\text{-}100B}$ and $\mathrm{M}_{77D\text{-}100B}$. Same considerations are valid for the case of the 100 % substitution of the fine fraction, where a decrease of 19% in the peak strength should be compared against a reduction of 12.8% for mixture $\mathrm{M}_{77D\text{-}0}$.

The effect of the quality of the natural and recycled aggregate on the strength reduction is confirmed by the tests of Sani et al. [2005], conducted using natural aggregate, prepared with a combination of common crushed limestone aggregate and natural sand, and recycled aggregate coming from C&D debris treated in an industrial crushing plant, whose specific composition is not determined. In this case the complete natural inert substitution led to a decrease in strength of about 40%.

Mixtures $\mathrm{M}_{77D\text{-}0}$ and $\mathrm{M}_{77D\text{-}100B}$ contain both 77% of recycled fine aggregates, derived by vibrated concrete blocks, however the presence of the total recycled coarse fraction in mixture $\mathrm{M}_{77D\text{-}100B}$ results to a worse compressive strength for the mixture.

Despite the observed concrete strength reduction, all mixtures containing recycled aggregates respect the threshold of class of strength 30 MPa prescribed for the characteristic cubic strength.

Mixtures $\mathrm{M}_{0\text{-}100B}$ and $\mathrm{M}_{77D\text{-}100B}$, prepared by 100% replacement of the coarse natural basalt aggregates with recycled basalt aggregates, show an evident, although not critical, reduction in terms of compressive strength. A possible explanation could be the assortment in the texture of the recycled basalt aggregates. The natural material, depending on its massive or vesicle structure, has a density in the order of 2700-3000 kg/m^3, a compressive strength of approximately 40-200 MPa and an elasticity modulus in the range 5000-14000 MPa.

The variability in the mechanical properties is mainly due to the lava layer depth [Pappalardo et al., 2013; Pappalardo and Mineo, 2016; 2017]. Natural basalt aggregates usually derive from the crushing of blocks of massive basalt, that has higher density than vesicular basalt, commonly used for the realization of architectural components due to its aesthetic qualities and workability (the so-called Etna Basalt Lava Stone "Occhio di Pernice"). Moreover, the traditional stone blocks used in low-cost buildings is often extracted from the superficial layer of the lava mantle, where the rock is characterized by the presence of voids and micropores due to magma gassing [Pappalardo et al., 2017]. Figure 7 shows the variation of the porosity of Etna basalt with the extraction depth, when different classes of porosity are considered. On the contrary, high quality constructions and stone paved road are usually made using square blocks and thick plates of massive basalt. It should now be obvious how the demolition waste can contain basalt components with very different properties. In spite of these uncertainties, recycled basalt aggregates possess high-level qualities, that make them ideal for the production of

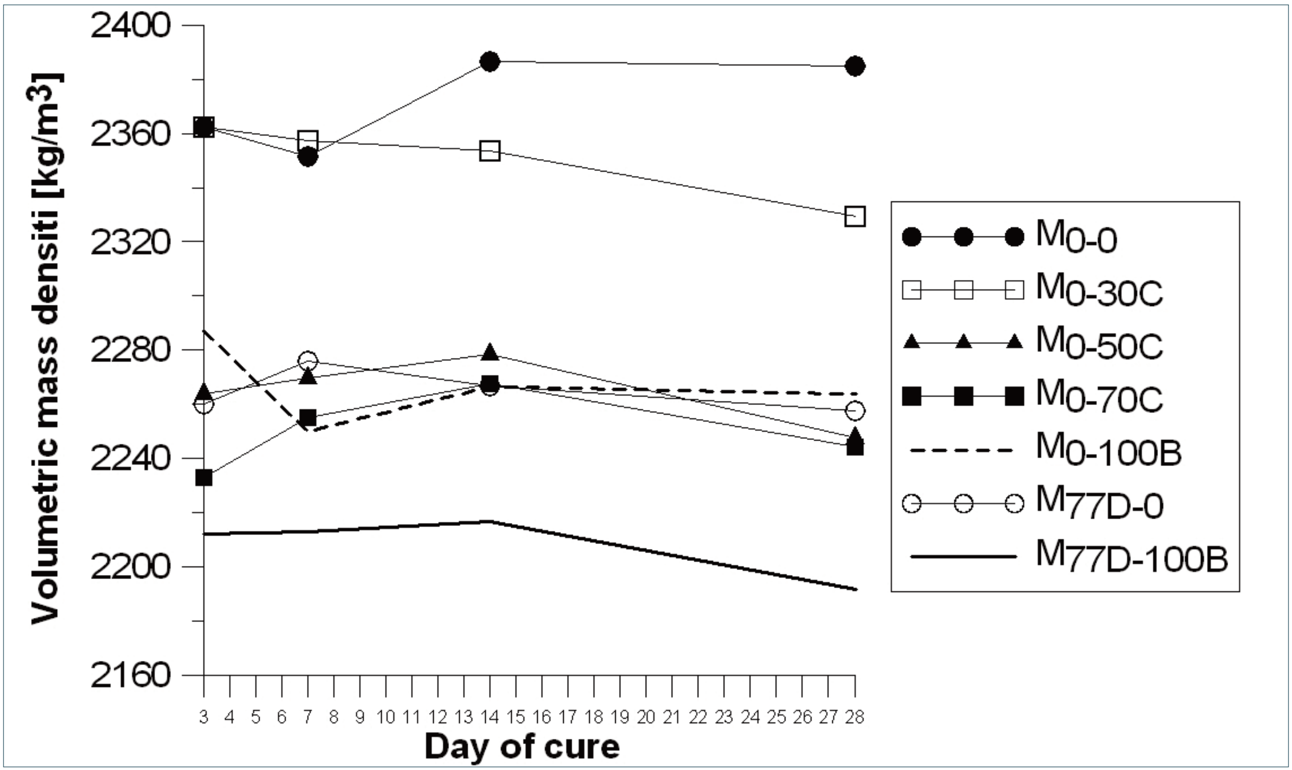

FIGURE 5. Density of fresh and hardened concrete.

Volumetric mass density (kg/m^3)							
Age (day)	M_{0-0}	M_{0-30C}	M_{0-50C}	M_{0-70C}	M_{0-100B}	M_{77D-0}	$M_{77D-100B}$
fresh	2335	2413	2292	2385	2232	2275	2225
3	2362	2362	2264	2233	2287	2260	2212
7	2351	2357	2270	2255	2250	2276	2213
14	2387	2353	2278	2267	2266	2266	2216
28	2385	2329	2247	2244	2264	2257	2192

TABLE 8. Volumetric mass density ρ of the mixtures.

high-level recycled aggregate concrete.

The average flexural strength σ_f and the average tensile strength σ_t at 28 days of cure together with the corresponding variations w.r.t. the control mixture $M_{0\text{-}0}$ are reported in Table 10. The results are also illustrated in Figures 8(a) and 8(b). The maximum value of the coefficient of variation was found to be 9.3%.

The data confirm the trend characterizing compressive, tensile and flexural strength, reported in the existing literature. Mixtures $M_{0\text{-}100B}$ and $M_{77D\text{-}100B}$, prepared by 100% replacement of the coarse natural basalt aggregates with recycled basalt aggregates, exhibit a reduction of the order of 17%. Mixture $M_{77D\text{-}0}$ develops the lower flexural strength, 31% lower than the reference one.

4.3.3. Modulus of elasticity

Figure 8(c) shows the average of the modulus of elasticity for all the mixes. The variation w.r.t. the control mixture, reported in Table 11, is decisively

Compressive strength σ_c (MPa) and variation Δ (%) w.r.t. M_{0-0}								
Age (day)	3		7		14		28	
	σ_c	Δ	σ_c	Δ	σ_c	Δ	σ_c	Δ
M_{0-0}	16.9	0.0	25.9	0.0	35.8	0.0	40.0	0.0
M_{0-30C}	19.6	+16.0	29.5	+13.9	35.8	+2.9	38.8	-3.0
M_{0-50C}	12.8	-24.3	21.0	-19.0	36.0	-21.7	33.7	-15.9
M_{0-70C}	12.8	-24.6	22.0	-15.1	29.0	-18.9	31.6	-21.1
M_{0-100B}	14.3	-15.4	23.0	-11.0	29.5	-17.1	32.4	-19.6
M_{77D-0}	13.4	-21.0	24.1	-6.8	29.7	-17.1	34.9	-12.8
$M_{77D-100B}$	11.6	-31.4	22.5	-13.2	28.8	-19.6	33.1	-17.3

TABLE 9. Compressive strength of concrete mixtures at different ages of cure and percentage of increment/decrement with respect to the reference value of the control mixture M_{0-0}.

lower for the Young modulus than the strength and limited to 3.6%. The maximum coefficient of variation for the data set was found to be 5.6%.

The analysis conducted by Silva et al. [Silva et al., 2016] shows that the elasticity modulus of recycled aggregate concrete tends to decrease significantly with increasing recycled aggregate content. Even when the compressive strength of the recycled aggregate concrete is equivalent to that of a conventional concrete, its modulus of elasticity tends to be lower. The same findings can be found in [Thomas et al., 2016], where recycled aggregate concrete is made from precast wastes. The authors observed that the influence of recycled aggregate is more evident on the elastic modulus rather than the compressive strength. A loss of stiffness of the concrete of 9% is observed for a sub-

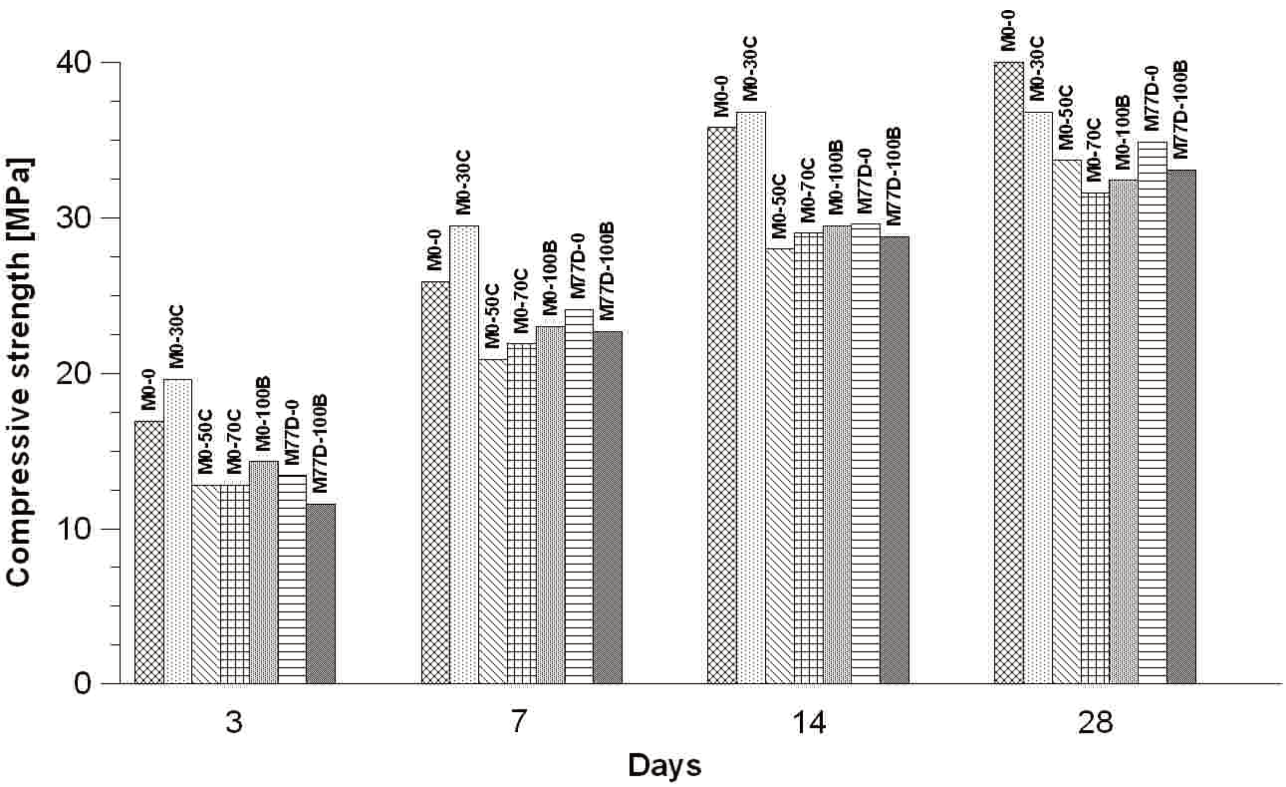

FIGURE 6. Concrete uniaxial compression strength.

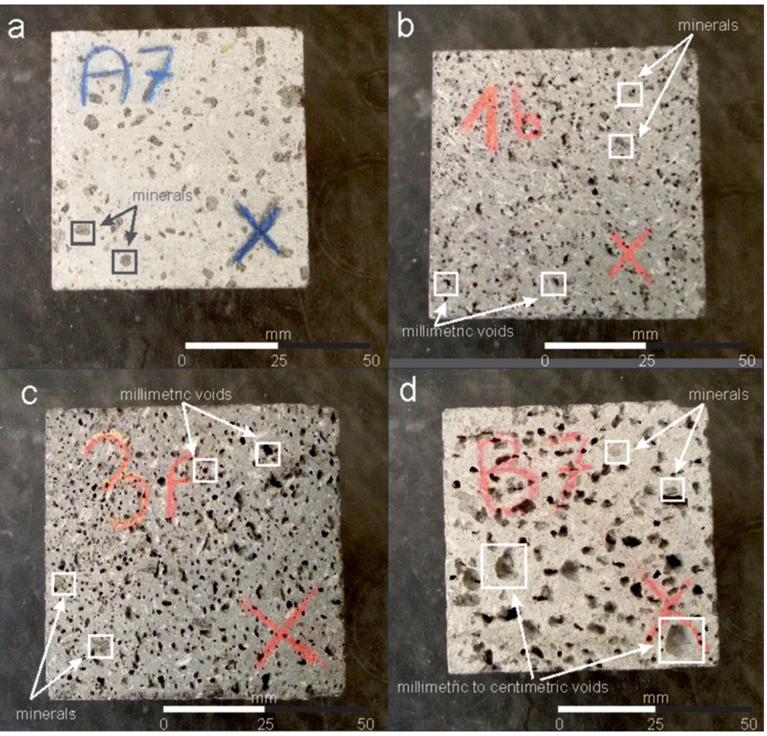

FIGURE 7 Etna basalt. (a) Class I: massive specimens with no visible vesicles. (b), (c) class II: vesicular specimens with millimetric voids; (d) Class III: vesicular specimens with millimetric to centimetric voids. From Pappalardo and Mineo[Pappalardo and Mineo, 2016].

Reduction of the water/cement ratio and consequent loss of stiffness is typical when concrete recycled aggregates are used; the higher the aggregate replacement ratio, the higher the water absorption and consequently the lower the water/cement ratio. For a fixed cement content in the unit volume this translates to a drastic reduction of the concrete stiffness.

Further considerations, concerning the relationship between modulus of elasticity and compressive strength of recycled aggregate concrete, can be found in the review paper by Silva et al [Silva et al., 2016], where the need for further research on the influence of the increasing amount of a given, high quality, recycled aggregates is highlighted.

5. CONCLUSIONS

This paper investigates the use of recycled materials for sub-road construction and concrete structural applications. Although the individual base materials considered for road sub-base mixes do not meet the ANAS reference parameter of Los Angeles resistance to fragmentation, they perform satisfactorily under compaction and lift, mix R_2 showing the best performance. The considered mixes allow the optimization of the reuse of materials from C&D waste. Owing to their good mechanical properties, the mixes may be used in road sub-base construction, even if limited to minor technical importance works [da Conceição Leite et al., 2011]. The sand grading curve may be improved to meet the requirements of the existing specifications by the addition of a low percentage of natural sand of suitable

Flexural and tensile strength (MPa) and variation Δ (%) w.r.t. $M_{0\text{-}0}$				
Age (day)	28			
	σ_f	Δ	σ_f	Δ
$M_{0\text{-}0}$	3.73	0.0	2.89	0.0
$M_{0\text{-}30C}$	3.71	-0.5	2.98	3.1
$M_{0\text{-}50C}$	3.05	-18.0	2.72	-5.9
$M_{0\text{-}70C}$	3.39	-9.1	3.03	4.8
$M_{0\text{-}100B}$	3.65	-2.1	2.38	-17.6
$M_{77D\text{-}0}$	2.56	-31.4	2.65	-8.3
$M_{77D\text{-}100B}$	3.08	-17.4	2.37	-18.0

TABLE 10 Flexural (σ_f) and tensile (σ_t) strength of concrete mixtures at the age of 28 days and percentage of increment/decrement with respect to the reference value of the control mixture $M_{0\text{-}0}$.

stitution of 100% of the coarse aggregate.

Nevertheless, the output of this research work shows the opposite trend. The reason possibly lies in the basaltic nature of the recycled aggregates, especially in the case of mixtures $M_{0\text{-}100B}$ and $M_{77D\text{-}100B}$. Recycled basaltic aggregate does not affect the water/cement ratio.

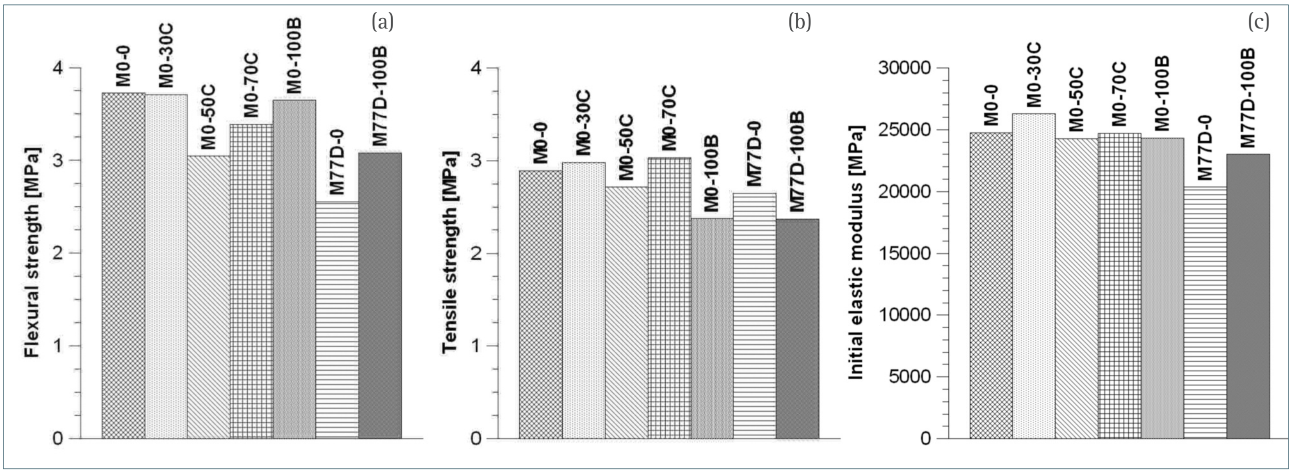

FIGURE 8. (a) Concrete flexural strength σ_f. (b) Concrete uniaxial tensile strength σ_t. (c) Concrete initial elasticity modulus.

grain size. Regarding the application in concrete manufacture, the obtained experimental results confirm the requirements of current Italian legislation on recycled construction materials, and demonstrate how the mixture $M_{0\text{-}30C}$, prepared by 30% coarse recycled concrete aggregates outperforms other mixtures in terms of compressive, tensile strength etc.

However, mixtures $M_{0\text{-}50C}$ and $M_{0\text{-}70C}$, containing 50% and 70% respectively of coarse recycled concrete aggregates perform slightly worse than mixtures $M_{0\text{-}100B}$ and $M_{77D\text{-}100B}$, containing 100% of coarse recycled basalt aggregates. In any case, the mixtures respect the limit imposed by the class of the designed concrete. Therefore, the use of recycled concrete aggregates deriving from structural concrete with basaltic fine and coarse aggregates can be considered for the preparation of admissible structural concrete and can be used with confidence for low-intensity load applications. Mixtures $M_{0\text{-}100B}$ and $M_{77D\text{-}100B}$, prepared with 100% replacement of the coarse natural basalt aggregates with recycled basalt aggregates present a small, non critical, reduction in terms of compressive strength and overall mechanical properties. Uncertainties may be introduced by the nature of the source of the recycled basaltic aggregates.

Mixtures $M_{0\text{-}100B}$ and $M_{77D\text{-}0}$ are characterized by a replacement level of 77% of the fine fraction of the aggregates. The comparison of their strength to the strength of mixture $M_{77D\text{-}100B}$ shows that the substitution of the fine fraction does not introduce any improvement and it is of scarce influence with respect to the role played by the recycled coarse fraction. The results obtained from mixture $M_{77D\text{-}0}$ suggest that the presence of recycled vibrated blocks sand introduces a brittle behavior in the material. However, as it was observed in [Fan et al., 2016], the production process of fine aggregates is important, because the crushing process can significantly influence the quality of the aggregates. Concrete with recycled aggregate produced by repeating the crushing process until the required particle size is obtained perform better than the ones with

Young modulus E (MPa) and variation Δ (%) w.r.t. $M_{0\text{-}0}$							
Age (day)				28			
Mix	$M_{0\text{-}0}$	$M_{0\text{-}30C}$	$M_{0\text{-}50C}$	$M_{0\text{-}70C}$	$M_{0\text{-}100B}$	$M_{77D\text{-}0}$	$M_{77D\text{-}100B}$
E	26257	26567	26780	26054	25935	25938	25306
Δ	0.0	1.2	2.0	-0.7	-1.2	-1.2	-3.6

TABLE 10. Young modulus of the mixtures at the age of 28 days and percentage of increment/decrement with respect to the reference value of the control mixture M_{0-0}.

fine recycled aggregate produced simultaneously with recycled coarse aggregate. This aspect will be the subject of future investigations.

Some expedients, investigated by other authors, could be introduced to improve the performance of concrete with recycled basalt aggregates. For instance, in addition to the superplasticizer, fly ash or silica fume could be used as a cement replacement to improve the mechanical properties [Ajdukiewicz and Kliszczewicz, 2002; Misra et al., 2005; Tangchirapat et al., 2010; Mukharjee and Barai, 2015], with a beneficial effect also on the service life of recycled aggregate concrete structures, because the presence of fly ash reduces the carbonation and chloride ion penetration depths and consequently introduces a delay in the reinforcement corrosion [Corinaldesi and Moriconi, 2009b], also lowering the drying shrinkage and creep [Kou et al., 2007; Kou and Poon, 2009]. Steam-curing could be adopted to reduce the porosity [Gonzalez-Corominas et al., 2016].

The overall results presented in the paper encourage future research work on the properties of recycled aggregates of basaltic nature, with particular interest in their durability and damaging behavior.

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