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Modulus of elasticity of concretes produced with basaltic aggregate

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Abstract. Basalt is a type of volcanic rocks, grey to black in colour, contains less than 20% quartz, 10% feldspathoid, and at least 65% of the feldspar of its volume. Basalt is considered an igneous rock with fine grains due to the rapid cooling of lava. Basaltic rocks have been widely used as aggregate for various purposes. The study presented in this paper was carried out on basalts that are widespread in the Madeira Island of Portugal and that comprise the major source of local crushed rock aggregates. This paper discusses an experimental programme that was carried out to study the effects of basaltic aggregate on the compressive strength and modulus of elasticity of concrete. For this purpose, cylinder specimens with 150×300 mm dimensions and prism specimens with 150×150×375 mm dimensions were cast. The experimental programme was carried out with several concrete compositions belonging to strength classes C20/25, C25/30, C30/37, C40/50 and C60/75. The Eurocode 2 indicates the modulus of elasticity should be 20% higher when the aggregates are of basaltic origin, however results showed significant differences and a correction is proposed.

Keywords: basaltic aggregates; modulus of elasticity; commercial concrete; Eurocode 2

1. Introduction

In many reinforced concrete structures applications, to estimate the material properties such as compressive strength and modulus of elasticity (MOE) is very important to meet design requirements. The only engineering property of concrete that is routinely specified is the characteristic compressive strength, frequently being other properties estimated based on the compressive strength value. However, the value of the MOE used in design is fundamental to all analysis with regard to stiffness of elements. For example, the MOE of normal and high strength concrete is a key parameter in structural engineering, and this parameter helps to determine the

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static and time-dependent deformation and system behaviour. It is also related to the assessment of other key processes such as creep, shrinkage, crack propagation and control in both reinforced concrete and prestressed concrete. Despite its importance, the MOE is not usually measured as it is time-consuming and expensive. The common practice is to estimate it using empirical relationships, based on various codes of practice. Such models often link the MOE with compressive strength, which essentially eliminate the need for going through laborious and time-consuming direct measurements from load-deformation curve.

In Portugal, although volcanic rocks are commonly used as concrete aggregates for concrete in Madeira Island, they are never used in the Mainland. In fact, Madeira Island is an island with volcanic origin and the aggregates used in the production of concrete had volcanic origin. Nonetheless, the information about the mechanical properties of basaltic aggregate concrete of Portuguese volcanic rocks is rather scarce. Hence, the MOE of the concrete used in the Madeira Island is usually assumed through the Eurocode 2 (2004), i.e., MOE is 20% higher than the reference one (quartzite aggregates).

However, the concrete can be produced by aggregates from different volcanic products: lava flows, pyroclastic materials, and etc. Virtually all volcanic rocks are able to be transformed in various sizes or diameters, through natural processes such as erosion or by using means artificial as mechanical fragmentation. Being aware that in Madeira Island concretes are made with basaltic aggregates, this study assessed the accuracy of the ratio used in Eurocode 2 (2004) to predict MOE. This study was carried out with several commercial concrete compositions produced with basaltic aggregates belonging to strength classes C20/25, C25/30, C30/37, C40/50 and C60/75.

2. Basalt as aggregate

Basalt is the most common type of extrusive igneous rock and somewhat common rock type at the Earth’s surface. Most basalts are volcanic in origin and were formed by the rapid cooling and hardening of the lava flows. Although, most basalts are extrusive rocks, cooled at Earth’s surface, there are some intrusive basalts, having cooled inside the Earth’s interior. Basalt is low in silica content, and comparatively rich in iron and magnesium (Anderson 2002). The mineralogy and texture of basalts vary with cooling history and with chemical composition. With slow cooling, crystals grow to large sizes reaching few millimetres. In basaltic melt, diffusion may limit the rate at which a given crystal-liquid boundary can move because the crystals differ in composition from the melt. If crystallization is forced at a rapid rate by rapid cooling, either the crystals will have high ratios of surface area to volume (needles, plates) or many seeds (nuclei) will develop. Crystals which grow rapidly under strongly supercooled conditions have different compositions from those which form if slower cooling prevails. Consequently, the same basalt flow may contain different minerals in variously cooled parts of the flow. Many physical properties of basalt have been measured in the field and laboratory, making it one of the best-characterized rock types. However, physical properties of basalts vary greatly because of the range of textures and compositions. Flowing temperature of basalt ranges from 1000 to 1220°C. The crushing strength and cohesive strength of cold basaltic rocks are 170-220 MPa and 32-44 MPa, respectively (Anderson 2002, Ibrahim *et al*. 2009, Ingrao *et al*. 2014).

Basaltic rocks are used extensively as engineering materials including aggregates for Portland cement concrete and asphaltic concrete, rock fill for dams and breakwaters, material for railroad ballast and highway base courses (Goodman 1993). The quality of the aggregates primarily

Table 1 The proportions of the basaltic aggregate concrete mixes

Mix	Cement (kg/m^3)	Fine sand (kg/m^3)	Coarse sand (kg/m^3)	Fine gravel (kg/m^3)	Coarse gravel (kg/m^3)
A1	305	640	368	541	413
A2	355	571	624	716	0
A3	375	571	624	716	0
B1	244	1179	0	386	575
B2	244	1179	0	386	575
B3	255	1195	0	399	581
B4	297	1204	0	421	608
B5	402	977	66	392	584
SCC*	412	609	397	475	203
PS	385	377	442	0	1211

Mix	Water (kg/m^3)	Admixture (kg/m^3)	*w/c*	D_{max} (mm)	Commercial strength class	Slump (mm)
A1	210	3.65	0.69	22	C20/25	130
A2	225	4.26	0.63	11	C25/30	140
A3	225	4.47	0.6	11	C30/37	130
B1	154	3.00	0.71	20	C20/25	170
B2	154	3.00	0.71	20	C20/25	160
B3	138	4.32	0.6	20	C25/30	140
B4	119	4.98	0.48	20	C30/37	120
B5	151	6.63	0.4	20	C40/50	140
SCC*	53	4.84	0.41	–	C60/75	–
PS	194	5.4	0.44	16	C40/50	–

*The SCC is composed by 134 (kg/m^3) of fly ash besides the proportions in Table 1. As the binder comprises 70% cement and 30% fly ash by volume, meaning a water/binder 0.31. The fresh properties tests for SCC were performed all in accordance with EN 12350-8 (2010), EN 12350-9 (2010), EN 12350-10 (2010), EN 12350-11 (2010) and it is determined the scattering class-SF3, the viscosity class-VF1 and segregation resistance class by sifting-SR2 (Aslani *et al*. 2014a, b, Aslani and Nejadi, 2012a, b, c, d, Aslani and Maia 2013).

depends on the properties of source rock. Hartley (1974), Ramsay *et al*. (1974), Lees and Kennedy (1975), Kazi and Al-Mansour (1980), Smith and Collis (2001), Cao *et al*. (2013), and Ingrao *et al*. (2014) have addressed the many geological factors (petrographical composition, texture, particle shape, pores, etc.) that affect the mechanical degradation of aggregates. The texture of a rock is an additional and complex factor affecting strength. Changes in mineralogical composition and texture of basalts affect physico-mechanical properties and, therefore, their quality as aggregate. Published test results on the properties of basaltic rock aggregates indicate that these types of rocks improve quality and strength of concrete (Tasong *et al*. 1998, Ozturan and ve Cecen 1997, Konkol and Prokopski 2009, Piotrowska *et al*. 2014). On the other hand, basaltic rocks generally have higher unit weight than other rocks and, therefore, basalt aggregate has high relative density. They cause segregation and therefore difficulty in pumping of concrete (Fookes 1980, Neville 1995).

Bell (1998) indicated that rocks like basalts tend to produce angular fragments when crushed. Angular fragments may produce a mix which is difficult to work. That is, it cannot be placed easily and offers less resistance to segregation. Nevertheless, angular particles are said to produce a denser concrete. In general, strong and hard or brittle rocks produce a higher proportion of flakes than weak rocks, although the latter generate more fines in crushing (Smith and Collis 2001). According to Krumbein and Pettijohn (1938), the microtopography of aggregate particles reflects petrographic and environmental factors of the original material. This property affects frictional properties and intergranular slip in unbound aggregate and the adhesion of binders or cement. In concrete, surface roughness is required for a satisfactory bond between aggregate and cement or asphalt, except that carbonate rock particles bond well with cement paste even when smooth (Franklin and Dusseault 1991). Basalts are also potential rocks from the point of alkali-silica reaction. Fookes (1980) gave examples of aggregate material that causes alkali-aggregate reaction. They are cherty limestone and mudstone, and some volcanic rocks having acidic or acidic-intermediate character. Arnould (1997) indicated that active alkalines content of basaltic rocks is important. In addition, according to Wakizaka (2000), volcanic glass existing in some volcanic rocks can cause alkali-silica reaction.

3. Experimental study

3.1 Materials and mix compositions

In order to meet the proposed objectives, specimens were collected from a total of ten mixes. Among the mixes, eight mixes correspond to commercial conventional concretes produced in two different concrete plants in the Madeira Island (three mixes were from the concrete plant A and five from the concrete plant B). Specimens were also collected from a self-compacting concrete mix (named ‘SCC’). This SCC mix was produced by a third different concrete producer.

In order to check the influence of the source of the basaltic aggregate, the tenth mix was made with basalt aggregates coming from the Porto Santo Island (an island that belongs to the Madeira Archipelago). This tenth mix (named ‘PS’) was a conventional concrete and it was produced in the laboratory (it was not a commercial concrete composition).

All the mixes were made with CEM II/A-L 42.5R (EN 197-1 2002) which is a Portland cement with 6-20% limestone filer with high early strength. In regarding to the aggregates, each concrete plant used aggregates coming from its own stone-quarry, i.e. there were four different sources of aggregates (three from aggregate plants in the Madeira Island and one from the Porto Santo Island). Nevertheless, concrete producers used two crushed gravels and two sands to produce their concretes. Table 1 presents the information provided by producers for each mix, namely constituent materials proportions, commercial compressive strength class and the consistency measured by the slump test (EN 12350-2 2009).

3.2 Specimens’ preparation and curing conditions

The experimental programme test for each mix was carried out in six cylindrical specimens of 150 mm diameter and 300 mm height. In order to compare results of MOE measured in cylindrical specimens with prismatic specimens, two prismatic specimens with square basis with 150 mm

Fig. 1 Cutting the prismatic specimen

edge and 750 mm height were collected for mix B1. Polyurethane moulds belonging to Regional Civil Engineering Laboratory, all calibrated, waterproof and non-absorbent were used.

Casting and curing of the specimens were conducted in accordance with EN 12390-2 (2009). Each mould was filled into two layers and compacted by mechanical vibration with a needle vibrator. The concrete was compacted after placing the mould in order to obtain full compaction without segregation. According to EN 12390-2 (2009), the specimen in the mould may leave between 16 and 72 hours, protected from shock, excessive vibration and dehydration at 20±5°C. For samples A1 and PS the test specimens were within the mould until the age of 48 hours. As for the remaining samples, the samples were within the mould until the age of 24 hours.

After demoulding, the specimens were placed in water at a temperature of 20±2°C in Regional Civil Engineering Laboratory facilities. The preparation of the specimens (smooth cylindrical basis and cut prismatic specimens) was performed 5±1 days before tests. During its preparation, no specimen was out of water more than 60 minutes. As the two prismatic specimens had length of

Table 2 The average mass of the specimens (kg)

Mix	Commercial Strength Class	Cylinder
A1	C20/25	12.7±0.1
A2	C25/30	12.8±0.0
A3	C30/37	12.9±0.0
B1	C20/25	13.1±0.0
B2	C20/25	13.3±0.1
B3	C25/30	13.4±0.1
B4	C30/37	13.5±0.0
B5	C40/50	13.5±0.0
SCC	C60/75	13.1±0.1
PS	C40/50	13.9±0.0

750 mm, it was necessary to cut these specimens in order to get two specimens with 370 mm in length (as shown in Fig. 1).

3.3 Dimension and mass of specimens' measurement

MOE tests were carried out at the age of 28 days. Thus, at the age of 28 days specimens were removed from the water and with slightly damp towel excess water and any extra material from the surfaces of the specimens were removed. Then, the size and mass of all specimens were measured (Table 2). All the measurements satisfied the EN 12390-1 (2012) requirements.

3.4 Compressive strength tests

The basaltic aggregate concrete compressive strength tests have been done based on the EN 12390-4 (2003). The procedure of this test in EN 12390-4 is summarized in the preparation and positioning of test specimens, load application, assessment of the type of rupture and presenting the results. The compressive strength for all mixes was performed in six cylindrical specimens. In three cylindrical specimens compressive strength test was done without the MOE test being performed (the compressive strength is required for determining the MOE) and in the reaming three specimens the compressive strength test was done after the MOE test being performed.

3.5 Modulus of elasticity tests

The MOE was determined according to the Portuguese specification LNEC E397 (1993). The tests have been done on three cylindrical specimens and on four prismatic specimens (as shown in Fig. 2). For the B1 mix all four prismatic test specimens with a square base of 150 mm and 370 mm edge length were also tested.

According to the Portuguese specification LNEC E397 (1993), an initial stress which corresponds to a stress in a range of 0.5 to 1.0 MPa is applied to specimen. Then specimen is loaded up to 30% of the concrete strength. Deformation is measured between the initial stress and the stress of 30% of the concrete strength. Loading cycles are repeated until the difference of deformation between two consecutive cycles lower than 10-5 m/m (see Fig. 3).

(a) (b)

Fig. 2 (a) Placement of extensometer and (b) modulus of elasticity test

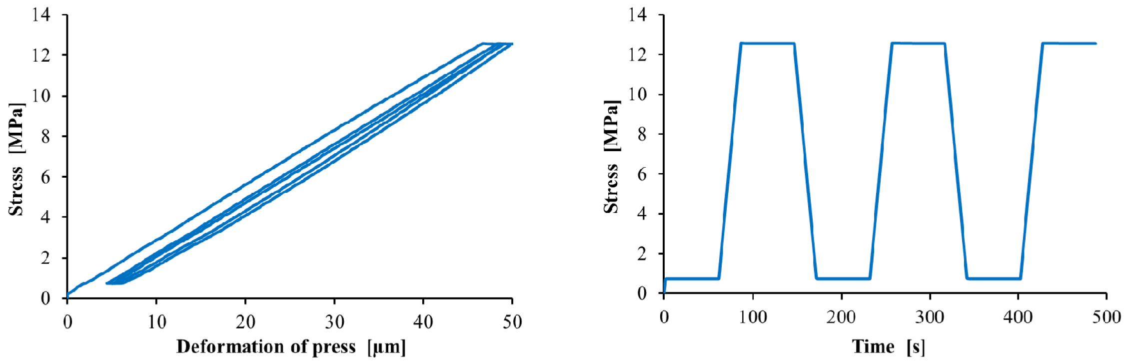

Fig. 3 Determining MOE with loading cycles: (a) deformation and (b) time

4. Experimental results

4.1 Modulus of elasticity results

According to EN 12390-3 (2009), the compressive strength is calculated from equation (1), where f'_c is the compressive strength (MPa), F is the maximum load at break (N) and A_c is the area cross section (mm^2) of the specimen in which the compression force has been applied.

$$f'_c = \frac{F}{A_c} \tag{1}$$

According to the Portuguese specification LNEC E397 (1993), the MOE is determined from the Eq. (2) where E_c is the MOE in compression (GPa), σ_a is the applied stress (MPa) which corresponds to 30% of the concrete strength, σ_b is the initial stress (MPa), $\varepsilon_{a,n}$ is the strain corresponded to σ_a stress measured at the n^{th} charge cycle and $\varepsilon_{b,n}$ is the strain corresponded to σ_b stress measured at the n^{th} charge cycle.

$$E_c = \frac{\Delta\sigma}{\Delta\varepsilon} = \frac{\sigma_a - \sigma_b}{\left(\varepsilon_{a,n} - \varepsilon_{b,n}\right)} 10^{-3} \tag{2}$$

Table 3 presents the MOE mean values and the corresponding standard deviation obtained for the different mixes. It is also reported in Table 3 the given MOE in Eurocode 2 for concrete produced by quartzite aggregate (reference in Eurocode 2) and basaltic aggregate.

Comparison of measured MOE results with Eurocode 2 shows that the results are not in an agreement with given values of Eurocode 2. In fact, according to the Eurocode 2 a concrete produced with basaltic aggregates shall have a MOE approximately 20% higher than a concrete produced with quartzite aggregates, however results presented in Table 3 show that MOE of the concretes produced with basaltic aggregate from Madeira Island are markedly lower (about 13%) than concretes produced with quartzite aggregates.

Such difference of the MOE in the calculation leads to a large errors in the calculation of deformation of the structures, especially if the value of the MOE is the one predicted for concretes produced with basaltic aggregates. The MOE of the SCC composition showed similar difference

Table 3 MOE obtained for the concretes studied and the given values of the Eurocode 2 for the MOE produced with quartzite and basalt aggregates

Mix	Commercial Concrete Strength Class according to Eurocode 2	MOE associated of according to Eurocode 2 for the corresponding strength class (Gpa)		MOE measured (Gpa)
		Quartzite aggregates	Basaltic aggregates*	
A1	C20/25	30	36	25.2±0.8
A2	C25/30	31	37	26.0±0.0
A3	C30/37	33	40	27.1±0.4
B1	C20/25	30	36	25.6±0.3
B2	C20/25	30	36	25.4±0.4
B3	C25/30	31	37	27.7±0.6
B4	C30/37	33	40	28.6±1.1
B5	C40/50	35	42	33.3±0.5
SCC	C60/75	39	47	35.7±1.0
PS	C40/50	35	42	37.5±0.3

*According to the Eurocode 2 the MOE of basaltic aggregate concretes are 20% higher than the MOE of the quartzite aggregate concretes.

than others MOE of concretes produced with aggregates from the Madeira Island. For the concrete produced with aggregates of the Porto Santo Island one observes that the MOE is higher than the value of the reference MOE of a concrete produced with quartzite aggregates but still 11% lower than the reference value of the MOE in Eurocode 2 of a concrete produced with basaltic aggregates. Note that according with Table 2, the concrete specimens from PS presented markedly higher mass than the other ones. Therefore, one might speculate that the problem of the low MOE might be in the origin of the basaltic aggregate, i.e., probably basaltic aggregates used to produce concrete in the Madeira Island have considerably lower stiffness than the ones considered in the Eurocode 2.

In order to check if the specimen geometry affects the MOE value, the MOE was also evaluated for four prismatic specimens of the concrete B1. The value measured was 25.7±0.4 GPa which compared with value of 25.6±0.3 GPa measured in cylindrical specimens. Although more tests should be done to base these findings, by the results obtained one may expect that the specimen geometry does not affect the value measured of the MOE.

4.2 Prediction of the MOE of basaltic aggregate concretes using compressive strength results

According to the Eurocode 2 (2004), it is possible to predict the MOE for a concrete through its value of compressive strength though the Eq. (3). Being aware that Eq. (3) is for concretes produced with quartzite aggregate one shall multiply the result by 1.2 in order to predict

$$E_{cm} = 22\left(\frac{f_{cm}}{10}\right)^{0.3} \quad (3)$$

Table 4 MOE predicted though the concrete strength value by Eurocode 2

Mix	Compressive strength measured in cylindrical specimens (Mpa)	MOE predicted by Eq. (3) (Gpa)	MOE predicted by Eq. (3)×1.2 (Gpa)	Difference between the MOE predicted by Eq. (3)×1.2 and the MOE measured
A1	24.2±0.3	28.7	34.4	27%
A2	36.6±0.1	32.5	39.0	33%
A3	44.2±0.4	34.4	41.2	34%
B1	27.3±0.4	29.7	35.7	28%
B2	27.5±0.4	29.8	35.8	29%
B3	37.4±0.4	32.7	39.2	29%
B4	38.6±0.3	33.0	39.6	28%
B5	63.2±0.4	38.3	45.9	27%
SCC	71.3±1.8	39.7	47.6	25%
PS	50.3±0.8	35.7	42.9	13%

the MOE for concretes produced with basaltic aggregates.

Table 4 shows the application of the Eq. (3) for all mixes and the respective differences in relation to the value of the measured MOE.

As shown in Table 4, first of all, one observed that at the age of 28 days the concrete produced in the Madeira Island had substantially higher compressive strength than the value of the commercial concrete class. Besides, it is observed that values obtained using Eq. (3)×1.2 leads to similar results than reported in Table 3. That means that the Eq. (3)×1.2 is in agreement with associate values of MOE for the corresponding strength class in Eurocode 2. Thus, bearing in mind that concretes produced with basaltic aggregates from Madeira Island have MOE almost 30% lower than the predicted one by Eurocode 2 the following modification is proposed in Eq. (3) to predict the MOE of concretes produced with basaltic aggregates from Madeira Island (Eq. (4) and Fig. 4).

$$E_{cm,\mathrm{mod}} = 19\left(\frac{f_{cm}}{10}\right)^{0.3} \quad (4)$$

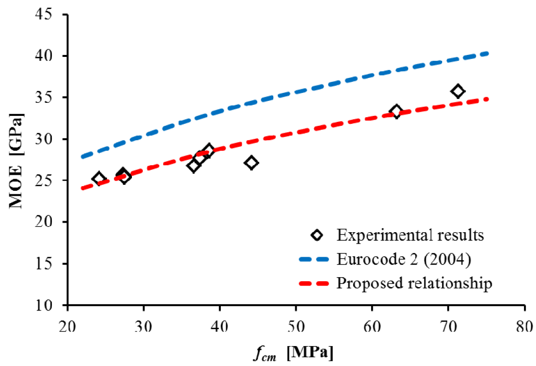

Fig. 4 Comparison of measured MOE results versus Eurocode 2 and the proposed relationship

As shown in Fig. 4, the proposed correction predicts MOE values reasonably close than experimental results, i.e., around 15% lower than reference values given by Eq. (3) for concrete produced with quartzite aggregates.

5. Conclusions

This investigation was mainly undertaken to evaluate the modulus of elasticity of concrete mixes having different sources of basalt aggregates from Madeira Island in Portugal. From this study the following conclusions can be drawn:

• The value of the modulus of elasticity for concrete produced with basaltic aggregates from the Madeira Archipelago, especially from the Madeira Island, is notably lower than the values indicated by the Eurocode 2 for concrete produced with basaltic aggregates.

• The value of the modulus of elasticity for concrete produced with basaltic aggregates from the Porto Santo Island was substantially closer (even though lower) to the given values of the Eurocode 2 than the ones of the concretes produced from basaltic aggregates from Madeira Island. In view of these results, it is concluded that probably that concretes produced with basaltic aggregate from Madeira Island have lower modulus of elasticity because the aggregates used probably have lower stiffness than the ones considered in the Eurocode 2.

• Values of the modulus of elasticity measured in prismatic specimens were similar than values obtained in cylindrical specimens. Although more tests are needed it seems that the specimen geometry does not affect the value of the modulus of elasticity obtained.

More research is strongly recommended in order to confirm the proposed correction on the predicting expression of the modulus of elasticity. Nevertheless, it is crucial that all stakeholders in construction activity in the Madeira Island, especially designers, constructors and concrete producers shall take into account that higher deformations might occur in concrete structures.

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References

Anderson, A. (2002), "Citing online sources: Basalt".

Arnould, M. (1997), "Alkali-reaction with silica alkaline aggregates result of recent researches in France", *Proceedings of the International Three Gorges Project Technical Seminar*, Yichang, China.

Aslani, F. and Maia, L. (2013), "Creep and shrinkage of high strength self-compacting concrete experimental and numerical analysis", *Mag. Concrete Res.*, **65**(17), 1044-1058.

Aslani, F. and Nejadi, S. (2012a), "Mechanical properties of conventional and self-compacting concrete: An analytical study", *Constr. Build. Mater.*, **36**, 330-347.

Aslani, F. and Nejadi, S. (2012b), "Bond characteristics of steel fibre reinforced self-compacting concrete",

Can. J. Civil. Eng., **39**(7), 834-848.
Aslani, F. and Nejadi, S. (2012c), "Bond behavior of reinforcement in conventional and self-compacting concrete", *Adv. Struct. Eng.*, **15**(12), 2033-2051.
Aslani, F. and Nejadi, S. (2012d), "Shrinkage behavior of self-compacting concrete", *J. Zhejiang. Uni. Sci. A.*, **13**(6), 407-419.
Aslani, F., Nejadi, S. and Samali, B. (2014a), "Short term bond shear stress and cracking control of reinforced self-compacting concrete one way slabs under flexural loading", *Comput. Concrete*, **13**(6), 709-737.
Aslani, F., Nejadi, S. and Samali, B. (2014b), "Long-term flexural cracking control of reinforced self-compacting concrete one way slabs with and without fibres", *Comput. Concrete*, **14**(4), 419-443.
Bell, F.G. (1998), *Engineering Geology*, 3rd Edition. Blackwell, Oxford.
Cao, W., Liu, S. and Feng, Z. (2013), "Comparison of performance of stone matrix asphalt mixtures using basalt and limestone aggregates", *Constr. Build. Mater.*, **41**, 474-479.
EN 12350-10 (2010), "Testing fresh concrete. Self-compacting concrete. L box test".
EN 12350-11 (2010), "Testing fresh concrete. Self-compacting concrete. Sieve segregation test".
EN 12350-2 (2009), "Testing fresh concrete. Slump-test."
EN 12350-8 (2010), "Testing fresh concrete. Self-compacting concrete. Slump-flow test".
EN 12350-9 (2010), "Testing fresh concrete. Self-compacting concrete. V-funnel test".
EN 12390-1 (2012), "Testing hardened concrete. Shape, dimensions and other requirements for specimens and moulds".
EN 12390-2 (2009), "Testing hardened concrete. Making and curing specimens for strength tests".
EN 12390-3 (2009), "Testing hardened concrete. Compressive strength of test specimens".
EN 12390-4 (2003), "Testing hardened concrete. Compressive strength. Specification for testing machines".
EN 197-1 (2011), "Cement. Composition, specifications and conformity criteria for common cements".
Eurocode 2 (2004), "Design of concrete structures - Part 1-1: General rules and rules for buildings", BS EN 1992-1-1: 2004: London, UK.
Fookes, P.G. (1980), "An introduction to the influence of natural aggregates on the performance and durability of concrete", *Q. J. Eng. Geo.*, **13**(4), 207- 229.
Franklin, J.A. and Dusseault, M.B. (1991), *Rock Engineering Applications*, McGraw-Hill, New York.
Goodman, R.E. (1993), *Engineering geology: Rock in Engineering Construction*, Wiley, New York.
Hartley, A. (1974), "A review of the geological factors influencing the mechanical properties of road surface aggregates", *Q. J. Eng. Geo.*, **7**(1), 69-100.
Ibrahim, A., Faisal, S. and Jamil, N. (2009), "Use of basalt in asphalt concrete mixes", *Constr. Build. Mater.*, **23**(1), 498-506.
Ingrao, C., Giudice, A.L., Tricase, C., Mbohwa, C. and Rana, R. (2014), "The use of basalt aggregates in the production of concrete for the prefabrication industry: Environmental impact assessment, interpretation and improvement", *J. Clean. Prod.*, **75**, 195-204.
Kazi, A. and Al-Mansour, Z.R. (1980), "Influence of geological factors on abrasion and soundness characteristics of aggregates", *Eng. Geo.*, **15**(3), 195-203.
Konkol, J. and Prokopski, G. (2009), "Relationships between fractal dimension and the mechanical and structural parameters of concretes with basalt aggregate", *Brit. Matrix Comp.*, **9**, 409-418.
Krumbein, W.C. and Pettijohn, J.F. (1938), *Manual of sedimentary petrography*, Appleton-Century-Crofts, New York.
Lees, G. and Kennedy, C.K. (1975), "Quality, shape and degradation of aggregates", *Q. J. Eng. Geo.*, **8**(3), 28-35.
LNEC E397 (1993), "Concrete-determination of elastic modulus in compression", *National Laboratory for Civil Engineering (LNEC)*, Lisbon, Portugal.
Neville, A.M. (1995), *Properties of Concrete*, 4th Edition, Pitman, London.
Ozturan, T. and ve Cecen, C. (1997), "Effect of coarse aggregate type on mechanical properties of concretes with different strengths", *Cem. Concrete Res.*, **27**(2), 165-170.
Piotrowska, E., Malecot, Y. and Ke, Y. (2014), "Experimental investigation of the effect of coarse aggregate

shape and composition on concrete triaxial behaviour", *Mech. Mater.*, **79**, 45-57.

Ramsay, D.M., Dhir, R.K. and Spence, I.M. (1974), "The role of rock and clast fabric in the physical performance of crushed-rock aggregate", *Eng. Geo.*, **8**(3), 267-285.

Smith, M.R. and Collis, L. (2001), "Aggregates: sand, gravel and crushed rock aggregates for construction purposes", *Geological Society, Engineering Geology Special Publication 17*, The Geological Society, London.

Tasong, W.A., Lynsdale, C.J. and Cripps, J.C. (1998), "Aggregate-cement paste interface. II: Influence of aggregate physical properties", *Cement Concrete Res.*, **28**(10), 1453-1465.

Wakizaka, Y. (2000), "Alkali-silica reactivity of Japanese rocks", *Eng. Geo.*, **56**(1), 211-221.

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