The Influence of Blast Furnace Slag on Abrasion Resistance for Road Concretes

L M Nicula¹, O Corbu¹,²,³* and M Iliescu¹
¹Technical University of Cluj-Napoca, Faculty of Civil Engineering, Romania
²Research Institute for Construction Equipment and Technology, Bucharest
³Center of Excellence Geopolymer& Green Technology (CEGeoGTech), School of Materials Engineering, University Malaysia Perlis, 01000 Kangar, Perlis, Malaysia, India

*E-mail: Liliana.nicula@infra.utcluj.ro; ofelia.corbu@staff.utcluj.ro; iliescu.mihai@staff.utcluj.ro

Abstract. In this study, the blast furnace slag was used as a mineral addition in the projected road concrete mixtures, and the blast furnace slag in the form of aggregate at 0/4 mm size was used as a percentage of 20%, 40% and 60%. Three concrete slag mixtures were compared with two other concrete mixtures made with conventional materials. Compared to the first conventional mixture, milled slag used as a 15% addition and compared to the second conventional mixture milled slag was used as a substitute for 13% of Portland cement mass. The wear / abrasion resistance was evaluated at the concrete age of 100 days, respectively 150 days. The results indicated the highest wear resistance for the mixture with 20% aggregates crushed from furnace slag, and the mixture with 60% substitution aggregates from furnace slag was observed the lowest resistance. The tendency of evolution of the wear resistance is similar to that of the compressive strength. Mixtures with the highest compression strength also recorded the lowest volume loss after the abrasion test (Böhme). Compared to the first mixture made with conventional materials, the wear resistance obtained in blast furnace slag mixtures is lower. However, mixtures with 13% ground slag and up to 40% of aggregates crushed from blast furnace slag have higher wear resistance compared to the second mixture made with conventional materials.

1. Introduction
The use of blast-furnace slag in optimum ratio, as mineral addition to the mass of the cement and as substitute of natural sand in road concrete mixtures can be a solution both for protecting the environment and for saving the natural resources. The ground surface as well as the aquatic ecosystem are affected by the cement industry that contributes with approximately 5-8% of the carbon dioxide issued globally, followed by the Sulphur dioxide SO₂ and the nitrogen oxides NOₓ, [1,2,3]. Also, the consumption of aggregates in concretes affects the natural aggregate reserves at a level of 20000 million of tons/year and an increase rate of 4.7% per year globally [4,5]. The blast-furnace slag is a secondary product obtained in the steel industry, through melting cast iron. By processing the sub-product of blast-furnace slag we obtain artificial materials that can be reused as prime materials in road constructions. The granulated blast-furnace slag is formed through the process of fast cooling in water of the melted slag, and it has a white colour, with dimensions of maximum 5 mm. The granular material resulted contains approximately 85-95% glass materials formed from calcium aluminium...
silicates, non-crystalline, [1,6]. The granulated and grounded blast-furnace slag has a latent hydraulic character, it is used as type II addition in concrete mixtures for the improvement of certain properties in compliance with the provisions of the SR EN 206:2002+A1:2007 [7] and SR EN 15167-1:2007 [8]. The non-granulated blast-furnace slag is obtained through the process of slow cooling in the air of the melted slag and presents a crystalline molecular structure, without any usage in the cements’ manufacturing, [9].

In compliance with the ACI 201.2R-08 [10]. Guide to Durable Concrete, the wear on the concrete surface can be caused by four different actions: due to human traffic on concrete floors, wear due to vehicular traffic with different types of tires and with steel wheels, abrasive materials carried by water (e.g. sand) affecting the hydrotechnical structures such as dams, and the high water velocity creating cavitation at the concrete surface [11]. The abrasion resistance is an important characteristic for the roads’ exploitation. The wear from the abrasion caused by traffic appears on the concrete surface due to friction, sideslips or slipping of vehicles in motion on the tread surface. The abrasion resistance of a concrete depends on the resistance of the composing materials and the liaison between the aggregate and the cement paste [11,12]. There are two point of views regarding the type of mathematical relations between the compressive strength and the abrasion resistance. The first point of view is that the compressive strength is the most important factor for the abrasion resistance and that between the two characteristics it is developed a linear relation [11,13-15]. While Atiş showed that between the compressive strength and the abrasion resistance there is a hyperbolic mathematical relation [1,12]. Liu and collaborators studied the influence of the w/c ration on the abrasion resistance in four different water/cement ratios, between 0.26-0.50. The increase of the abrasion resistance was registered in mixtures in which the w/c ratio decreased. These concretes had a lower porosity, a better liaison between cement paste and aggregate and an increased compressive strength [11,16]. The second point of view is that the abrasion resistance is not dependent on the compressive strength, this being influenced by the hardening conditions and the surface finishing technology [1,17-22]. Kevern et al. tested the abrasion resistance of concrete preserved in six different hardening regimes. The hardening regime was in air, the humid hardening was under plastic for 7 and 28 days, the hardening regime with oil-based protection, white pigment protection and the regime without protection for delayed evaporation. The hardening regime in humid environment with plastic protection contributed best to the densification of the concrete surface and in obtaining the best abrasion resistances due to the greenhouse effect [11,23]. Dhir showed that the long period of hardening in humid environment of 7 days, compared to 1 day and 4 days, influences the increase of the abrasion resistance [11,24]. Bakke et al. recommends the humid hardening of 5-7 days for improving the abrasion resistance [11,25].

This study considers a comparative analysis of the abrasion and compressive resistance between road concrete in which it was used the blast-furnace slag as powder and crushed aggregates at 0/4 mm and road concrete made of conventional materials. The results obtained between the two characteristics were graphically represented by a second-degree polynomial equation.

2. Materials and methods

2.1. Cement

The cement available type CEM I 42.5R was supplied by the cement factory LafargeHolcim Romania, having a Blaine surface of 4385 cm²/g and specific weight of 3.0 t/m³. The main characteristics of the cement are presented in Table 1, in compliance with the provisions of the standard SR EN 197-1:2011 [26], having the performances stated by the manufacturer in the declaration of performance [27].

| Characteristics              | Obtained values | Characteristics          | Declared values |
|------------------------------|-----------------|--------------------------|-----------------|
| Clincher-K (% of mass)       | 95÷100          | Calcination loss, (%)     | Max.5           |
| Auxiliary components, %      | 0÷5             | Insoluble residue, (%)    | Max.5           |

2
### Table 2. Characteristics of the granulated blast furnace slag.

| Characteristics                                      | Obtained values | Limits SR EN 15167-1:2007 |
|------------------------------------------------------|-----------------|----------------------------|
| Sum CaO+MgO+SiO2, %                                  | 8.05            | ≥ 2/3 %                    |
| Ratio (CaO+MgO)/SiO2, %                              | 1.3             | ≥ 1.0 %                    |
| Magnesium oxide MgO, %                               | 5.80            | ≤ 18%                      |
| Sulphides, %                                         | 0.58            | ≤ 2.0%                     |
| Sulphate, %                                          | 0.44            | ≤ 2.5%                     |
| Correct calcination loss for sulphides oxidation, %  | 0.00            | ≤ 3.0%                     |
| Chlorine, %                                          | 0.004           | ≤ 0.10%                    |
| Humidity content, %                                   | 6.85%           | ≤ 1.0%                     |
| Specific surface, cm²/g                              | 3520            | ≥ 2750                     |
| Content of alkalis in cement (Na₂O equivalent), %     | 1.0 %           | (0.5 ±1.2) %               |
| Activity index at 7 days, %                          | 58.48           | Min 45 %                   |
| Activity index at 28 days, %                         | 74.94           | Min 70 %                   |
| Content of tricalcium aluminate in cement C₃A, %     | 7.59            | (6 ±12) %                  |

2.2. **The additional constituents with cement characteristics (CSCC)**

The Laplante study shows that the ultrafine silica has an important contribution to the increase of the compressive strength and to the improvement of the abrasion resistance of the concrete [11,28]. Other authors as well reported that the inclusion of the ultrafine silica (SF) increased the abrasion resistance in concrete or mortar. Turk studied the abrasion resistance of self-compacted concrete in which the cement was partially replaced with fly ash (FA) or ultrafine silica (SF). The replacement percentages with (FA) were 25%, 30%, 35%, and 40%, while for the (SF) were 5%, 10%, 15%, and 20%. The results showed an increase of the abrasion resistance in mixtures with substitution of up to 15% (SF), while in the mixtures with fly ash the abrasion resistance decreased with the increase of the (FA) content, over 30%, [1,29] studied the effect of the ultrafine silica (SF) and the ground-granulated blast-furnace slag (GGBS) on the compressive strength and abrasion resistance at the age of 7, 28, 90 and 180 days on HVFA concrete (concrete with high level of substitution of 70% fly ash (FA)). The results showed the best abrasion resistances in mixtures with 50%(FA)+20%(SF) and for 50%(FA)+10%(SF)+10%(GGBS). Naik the effects of replacing the fly ash (FA) from class C on abrasion resistance of the concrete mixtures. There were chosen five levels of cement replacement, between 15% and 70%.

The results of the abrasion resistance could be compared to the control mixture for the replacement levels of 15% and 30%, but above these levels, the concrete did not obtain good abrasion resistances, [11,30].

In this study, it was used ground-granulated blast-furnace slag that was used as additional constituent with cement characteristics (CSCC) in road concrete mixtures. The granulated blast-furnace slag at 0/4 mm dimension was delivered by the company ArcelorMittal from Galați. After grounding the Blaine surface was established at a value of 5770 cm²/g, and the specific weight of 2.77...
t/m³, testing performed through this experiment. The other granulated blast-furnace slag characteristics resulted from the testing reports [31-34] performed by the supplier. The obtained values were analysed by comparison with the recommended standard SR EN 15167-1:2007 [8], see Table 2.

2.3. Aggregates

The used aggregates proportions were 32% sand (0/4 mm dimension sand) and 68% coarse aggregate. Selecting the type of coarse aggregates for their usage in concrete mixtures resistant to wear represented interest for researchers. The aggregate resistance to fragmenting was researched by Kiliç et al. on different types of crushed coarse aggregates, respectively on magmatic rock, basalt, quartzite, chalk and sandstone. The Los Angeles coefficient (LA) was determined for each type of rock. They noticed a strong correlation between the aggregate resistance and the concrete wear resistance. The mixtures in which the aggregate had inferior resistances suffered a greater loss in wear than those with aggregates resistant to fragmenting, [11,35]. Dhir investigated the effect of the maximum dimension of the aggregate on the abrasion resistance. Four maximum aggregate dimensions were tested: 5, 10, 20, and 40 mm. the test results showed that the abrasion resistance decreased with the increase of the coarse aggregate dimension, up to 20 mm, [11,36].

The selection the coarse aggregates used in this experiment took into consideration the provisions of the regulation NE 014:2002, [37], but also the conclusions of previous studies. Coarse aggregates were supplied from two different sources, the 4/8 mm dimension sort was crushed gravel pit aggregate, while the 8/16 and 16/25 sorts were crushed rock from dacite type quarry. The source of the used quarry aggregates is famous for the characteristics complying with the concrete requirements due to very good wear resistance (the micro-Deval coefficient $M_{\text{De}}$6) and the fragmenting resistance (the Los Angeles coefficient $L_{\text{A}14}$), [38, 39]. The non-granulated air-cooled blast furnace slag (ABS) artificial aggregate was supplied by the company Arcelor Mittal to substitute in different proportion the natural sand. The properties of the aggregate of blast furnace slag crushed at 0/4 mm dimension resulted from the report [40], based on the lab tests performed by the supplier. The volume mass of the used aggregates was determined in our university laboratory using the method established by the SR EN 1097-6: 2002 [41], the resulted values are presented in Table 3.

| Name_sort | NA_0/4 | ABS_0/4 | CA_4/8 | CA_8/16 | CA_16/25 |
|-----------|--------|---------|--------|---------|----------|
| $\rho$ (t/m³) | 2.7    | 2.59    | 2.68   | 2.66    | 2.67     |

In compliance with the standard SR EN 206+A1:2017, [7] both the natural aggregates and the blast furnace slag aggregates enter the category of current aggregates because they have the volume mass between (2.0 ÷3.0) t/m³. The granulometric curve of the aggregate total mixture followed a framing of the interior granularity area in compliance with NE 014-2002 [37] and in NE 012/1-2007 [42], see Figure 1. The testing procedure on aggregates complied with the normative references from SR EN 12620:2003 and SR EN 12620:2003+A1:2008 [43] and SR 667:2001 [44].
2.4. Chemical addition and water in mixture
The used additives were supplied by the company BASF Romania, the super-plasticizer additive MasterGlenium SKY 527 and the air-trainer additive Master Air 9060. The water from the concrete was taken from the water supply system of the city Cluj-Napoca, in compliance with SR EN 1008:2003 [45].

2.5. The mixtures proportion
There were a number of five mixtures in the first series of the experiment having the material quantities mentioned in Table 4. The first two control mixtures were made with Portland cement and with natural aggregates, and for the following three mixtures there were used ground-granulated blast furnace slag under 63 µm (GGBS) and crushed air-cooled blast furnace slag aggregate (ABS) with 0/4 mm dimension, in different proportions:

- **S 360c**, control mixture with 360 kg/m³ dosage of Portland cement and natural aggregates;
- **S 414c**, control mixture with 360 kg/m³ dosage of Portland cement and natural aggregates;
- **S 54/20**, mixture with 54 kg/m³ (GGBS) and 20% (ABS)₀/4 mm;
- **S 54/40**, mixture with 54 kg/m³ (GGBS) and 40% (ABS)₀/4 mm;
- **S 54/60**, mixture with 54 kg/m³ (GGBS) and 60% (ABS)₀/4 mm;

### Table 4. Material quantities in mixtures.

| Quantities                              | Mixtures [Kg/m³] |
|----------------------------------------|------------------|
|                                        | S 360 c | S 414 c | S 54/20 | S 54/40 | S 54/60 |
| Cement (C)                             | 360     | 414     | 360     | 360     | 360     |
| Ground-granulated blast furnace slag (GGBS) | -       | -       | 54      | 54      | 54      |
| Total binder (L)                       | 360     | 414     | 414     | 414     | 414     |
| W/Lw, (water/binder)                   | 0.44    | 0.41    | 0.41    | 0.43    | 0.43    |
| Aggregate                              | 1864    | 1831    | 1863    | 1810    | 1810    |
| Density in fresh state                 | 2380    | 2415    | 2444    | 2402    | 2402    |
| Super-plasticizer additive             | 3.60    | 4.14    | 4.14    | 4.97    | 4.97    |
| Air trainer additive                   | 1.08    | 2.07    | 2.07    | 2.07    | 2.07    |
Compared with the control mixture S\(_{360}\)c the ground-granulated blast furnace slag (GGBS) was brought as input to the cement mass in percentage of 15%, and compared to the control mixture S\(_{414}\)c the ground-granulated blast furnace slag (GGBS) substituted the cement in percentage of 13%. The natural sand was substituted with crushed air-cooled blast furnace slag (ABS) aggregate_0/4 mm with a dimension of 0/4 mm.

2.6. Methods

The wear resistance was tested on abrasive disk of the Böhme device, the brand Matest, presented in Figure 4, in compliance with the standard SR EN 1338:2004/AC:2006 [46], Annex H, through the determination of the volume loss. This method was used and by Orhan 2017 [47] in his study performed on road concrete. In each projected mixture there were performed 6 cubic specimens with a side of \(71 \pm 1.5\) mm for the wear test and 6 cubic specimens with a side of 150 mm for compressive strength. The specimens were kept for 24 h in air, afterwards they were removed from forms and then kept in water at a temperature of \((20\pm2)\) °C. At the age of 7 days, the 71 mm cubes and the 150 mm cubes were removed from water and they were kept in air, in a climatic chamber, at a temperature of \((20\pm2)\) °C and a humidity of \((65\pm5)\) %. From the age of 50 days, until the testing age of 100 days and 150 days, the specimens were placed in water at a temperature of \((20\pm5)\) °C. Afterwards, at the age of 100 days, a set of 3 specimens for each mixture with the 71 mm dimension were removed from water and prepared for the wear testing. The specimens were dried up to the constant mass at a temperature of \((105\pm5)\) °C, 20 gr of standard abrasive material was scattered on the testing track, the specimen was fixed in the device with the testing side on the track and a force of \((294\pm3)\) N was applied centrally. Each specimen was tested for 16 cycles, a cycle containing 22 rotations. After each cycle the disk was cleaned, the abrasive material replaced and the contact side was progressively rotated at 90°. The wear after 16 cycles, as an average of the lost volume \(\Delta V\), see the equation (1), the results fitted in the abrasion resistance class as in Table 5.

![Böhme device](image)

\[
\Delta V = \frac{\Delta m}{\rho}
\]

Where \(\Delta V\) (mm\(^3\)) represents the volume loss after 16 cycles, \(\Delta m\) (g) represents the mass loss after 16 cycles, and \(\rho\) (g/mm\(^3\)) represents the specimen density. The wear test was repeated on other three specimen sets at the age of 150 days, using the same procedure.

### Table 5. The abrasion resistance classes.

| Class | Marking | Conditions |
|-------|---------|------------|
| 1     | F       | No measured performance |
| 3     | H       | \(\leq 20000\) mm\(^3\)/5000 mm\(^2\) |
| 4     | I       | \(\leq 18000\) mm\(^3\)/5000 mm\(^2\) |
The compressive testing was performed with the type Advantest 9 hydraulic digital press, of 300tf in compliance with SR EN 12390-3:2002 [48], on 3 cubes of 150 mm for each mixture, with an age of 100 and 150 days. The 150 mm specimens were tested for compression and kept in water from the age of 50 days until the age of 100 days, respectively 150 days, were used as witness samples at 150 and 300 repeated freeze-thaw cycles.

3. Results and discussions
The volume loss results of the specimen tested at 100 and 150 days and the compressive strength are presented in Table 6 and in Figures 4 and 5.

Table 6. The volume losses from abrasion testing and the compressive strength at the age of 100 days, respectively 150 days.

| Mixture    | Δm (g)  | ρR (g/mm$^3$) | ΔV (mm$^3$) | f cm (MPa) |
|------------|---------|--------------|-------------|------------|
|            | 100d/150d | 100d/150d    | 100d/150d   | 100d/150d  |
| S 360c     | 27.73/25.80 | 0.002379/0.002300 | 11660/10833 | 85.83/87.78 |
| S 414c     | 32.85/29.63 | 0.002324/0.002323 | 14138/12860 | 81.46/80.96 |
| S 54/20    | 30.85/27.25 | 0.002375/0.002377 | 12986/11577 | 87.07/84.90 |
| S 54/40    | 31.65/28.75 | 0.002323/0.002323 | 13627/12376 | 80.85/79.38 |
| S 54/60    | 39.13/36.25 | 0.002378/0.002380 | 16454/15039 | 76.79/74.77 |

The volume loss evolution at the age of 100 and 150 days of the specimens tested for wear resistance registers a tendency inversely proportional with the results of the compressive strength, see Figures 4 and 5. The higher the compressive strengths, the smaller the volume losses of the tested specimens, as highlighted in the mixtures S 360c and S 54/20. The reverse situation can be seen in the mixtures S 414c, S 54/40 and S 54/60, smaller the compressive strengths led to higher volume losses for the tested specimens. However, it can be noticed a slight increase of the wear resistance (the volume loss decreases) in all mixtures once the age increases from 100 days to 150 days. This is attributed to the prolonged period of hydration of the binding agent in the made mixtures.

The volume loss after the abrasion test at the age of 100 days was smaller with 8.14% and with 9.98% at 150 days in the S 54/20 mixture, compared with the control mixture S 414c. The mixture S 54/40 has a good behaviour regarding the wear resistance, where it can be noticed a decrease of the volume loss with 3.76% at 150 days compared to the control mixture S 414c. While the volume loss at the age of 150 days increased significantly with 16.94% in the mixture S 54/60 compared with the control mixture S 414c.

Figure 4. Volume loss through wear,

Figure 5. Compressive strength.
Figures 6 a) and b) show the relationship between the compressive strength and the volume loss after abrasion testing at 100 and 150 days. It can be noticed that between the two characteristics a second-degree polynomial equation is developed, derived through regression, having a correlation coefficient (R value) very good.

\[
y = 41.941x^2 - 7269.6x + 327448 \\
R^2 = 0.8938
\]

![Graph a)](image1)

![Graph b)](image2)

**Figure 6.** The relationship between compressive strength and volume loss a) at 100 days, b) at 150 days.

The obtained results confirm those offered by Alaa M. R. [1] who also established a polynomial relationship and a correlation coefficient close to 0.9298 between the compressive strength and the depth loss.

4. Conclusions

In this study we tested the resistance to wear on three mixtures in which it was included the same quantity of 54 kg/m³ of grounded-granulated blast furnace slag (GGBS) as binding agent and three different percentages (20%, 40% and 60%) of air-cooled blast furnace slag aggregate (ABS) with a dimension of 0/4 mm that substituted the natural sand. The results were compared with two control mixtures made of different dosage of Portland cement. For the mixtures with blast furnace slag the quantity of (GGBS) became supplement of 15% of the mass of the cement compared with the first control mixture S 360c, but compared with the second control mixture, the cement quantity was substituted with 13% (GGBS).

A general conclusion from this performed study is that an increase of the compressive strength leads to an increase of the resistance to wear of the road concrete and, implicitly, a decrease of the mass loss after wear. Also, important factors positively influencing the resistance to wear are: aggregates resistant to fragmentation and wear, a low water/cement ratio and a hardening regime in the humid environment of at least 7 days.

The compressive strength and implicitly, the abrasion resistance for the two control mixtures were higher in the S 360c mixture compared with S 414c. These results are due to the fact that by increasing the cement dosage from 360 to 414 kg/m³ also increased the necessary quantity of water, but the quantity of aggregate was diminished in the S 414c mixture.

The best results were obtained for the mixtures S 54/20 and S 54/40, with 13% cement substitution with ground slag and with 20%, respectively 40% blast furnace slag aggregate, in which the abrasion resistance, at all ages, were higher than that of the control mixture S 414c. But, in the mixture in which it was substituted 60% blast furnace slag aggregate the wear resistance was lower than that obtained in the control mixture S 414c.
Between the two studied characteristics was developed a second-degree polynomial mathematical equation which shows a regression of the volume loss from the wear testing in compliance with the increase of the compressive strength.

The concrete mixtures made registered, at all ages, a volume loss smaller than \(18000 \text{ mm}^3/5000 \text{ mm}^2\), values that allowed the fitting in the abrasion resistance class 4 with marking I, in compliance with the classification in Table 5.

5. References

[1] Rashad A M, Seeem H E-D H and Shaheen A F 2014 International Journal of Concrete Structures and Materials 8(1) 69-81
[2] Rashad A M and Zeedan S R 2011 Construction and Building Materials 25 3098–3107
[3] National Air Quality Monitoring Network http://www.calitateaer.ro/public/assessment-page/pollutants-page/oxid-a2ot-page/index.html.
[4] Chendes R 2017 Experimental determinations regarding the reuse of concrete resulting from the demolition of buildings http://www.upt.ro/img/files/2016-2017/doctorat/teze/rezumat/Chendes_Remus_rezumatul_tezei_ro.pdf
[5] Bleishwitz R and Bahn-Walkowiak 2011 Minerals Engineering, 22
[6] Swamy R N 1986 Concrete technology and design. Cement replacement materials. London, U.K.: Surrey University Press, First publication 3
[7] *** SR EN 206:2002+A1:2017 Concrete-Part 1: Specification, performance, production and conformity
[8] *** SR EN 15167-1:2007 Ground granulated blast furnace slag for use in concrete, mortar and grout. Part 1: Definitions, specifications and conformity criteria
[9] User Guidelines for Waste and Byproduct Materials in Pavement Construction, Publication Number:https://www.fhwa.dot.gov/publications/research/infrastructure/structures/97148/bfs1.cfm
[10] American Concrete Institute ACI201.2R 2008 Guide to Durable Concrete, Michigan, USA
[11] Scott B D and Safiuiddin Md 2015 Concrete Research Letters, www.crl.issres.net 6(3)
[12] Papenfus N 2003 Applying Concrete Technology to Abrasion Resistance, Proceedings of the 7th International Conference on Concrete Block Paving, Sun City, South Africa
[13] Naik T R, Sing, S S & Hossain M M 1995 ACI Materials Journal 92(6) 649–650
[14] Naik T R, Singh S S & Ramme B W 2002 Journal of Materials in Civil Engineering 417–426
[15] Yen T, Hsu T, Liu Y W & Chen S H 2007 Construction and Building Materials 21 458–463
[16] Liu Y-W, Yen T and Hsu T-H 2005 Cement and Concrete Research 1814-1820
[17] Lengan B W, Joshi, R C & Ward M A 1990 Canadian Journal of Civil Engineering 17 19–27
[18] Nanni A 1989 ACI Materials Journal 86(53) 559–565
[19] Nazari A and Riahi S 2011 Energy and Buildings 43 2939–2946
[20] Riahi S and Nazari A 2011 Science China, Technological Sciences 54(9) 2349–2357
[21] Ytterburg R F 1971 Civil Engineering, ASCE 41(1) 68–71
[22] Nanni A 1989 Journal of Transportation Engineering, ASCE 114(6) 684–694
[23] Kevern J T, Schaefer V R and Wang K 2009 Journal of Testing and Evaluation 37(4) JTE101761
[24] Dhir R K, Hewlett P C and Chan Y N 1991 Materials and Structures 24 122-128
[25] Bakke K J 2006 Abrasion Resistance, Significance of Tests and Properties of Concrete and Concrete-Making Materials, ASTM STP 169D, Bridgeport, pp. 184-193
[26] *** SR EN 197-1:2011 Cement- Part 1: Composition, specification and conformity criteria common cements.
[27] Declaration of Performance no. CPR-043-AE, Portland Cement, Holcim SA.
[28] Laplante P, Aitcin P-C and Vezina D 1991 Journal of Materials in Civil Engineering 3(1) 19-28
[29] Turk K, & Karatas M 2011 Indian Journal of Engineering and Materials Sciences 18 49–60
[30] Naik T R, Singh S S and Hossain, M M 1995 ACI Materials Journals 92(6) 649-659

9
[31] Laboratory Test Report no. 848/ 25.08.2016, ArcelorMittal for granular slag.
[32] Laboratory Test Report ref. AHKRO 11755-6M/01.08.2018, ArcelorMittal for granular slag.
[33] Laboratory Test Report ref. AHKRO 11802-Z/25.09.2018, ArcelorMittal for granular slag.
[34] Laboratory Test Report ref. AHKRO 11806-A/10.0802018, ArcelorMittal for granular slag.
[35] Kiliç A, Atiş C D, Teşmen A, Karahan O, Özcan F, Bilim C and Özdemir M 2008 Cement and Concrete Composites 30(4) 290-296
[36] Dhiri R K, Hewlett P C and Chan Y N 1991 Materials and Structures 24 122-128
[37] xxx NE 014-2002, The norm for the execution of cement concrete road pavements in a fixed and sliding formwork system, of Romania.
[38] Laboratory Test Report no.545/03.04.2018, SC Grandemar SA.
[39] Laboratory Test Report no.956/ 30.06.2017, SC Grandemar SA.
[40] Laboratory Test Report No.706/13.07.2016, ArcelorMittal for artificial aggregates.
[41] xxx SR EN 1097-6:2002, Test for mechanical and physical properties of aggregates -Part 6: Determination of particle density and water absorption.
[42] xxx NE 012-1-2007, Code of practice for the manufacturing of concrete, of Romania.
[43] xxx SR EN 12620:2003 and SR EN 12620+A1:2008, Aggregates for concrete.
[44] xxx SR 667:2001, Natural aggregates and worked stone for roads.
[45] xxx SR EN 1008:2003, Mixing water for concrete.
[46] xxx SR EN 1338:2004/AC:2006, Concrect paving blocks. Requirements and test methods.
[47] Orhan K, Muhammet Vefa A, Metin Murtlu A 2017 Effect of fine aggregate abrasion resistance and its finess module on wear resistance of Portland cement pavements, https://www.researchgate.net/profile/Metin_Aydin2/publication/316636335/links/5908f027458515ebb495c5da/Effects-of-fine-aggregate-abrasion-resistance-and-its-finess-module-on-wear-resistance-of-Portland-cement-concrete-pavements.pdf.
[48] SR EN 12390-3:2002 Thesting hardened concrete-Part 3: Compressive strength of test specimens.