Proceedings of the XVII ECSMGE-2019
Geotechnical Engineering foundation of the future
ISBN 978-9935-9436-1-3

doi: 10.32075/17ECSMGE-2019-1001

XVII European Conference
ECSMGE 2019
Reykjavik
on Soil Mechanics
and Geotechnical Engineering

Shear strength characteristics and resilient moduli response of steel slag aggregates as recycled road construction materials

Caractéristiques de résistance au cisaillement et réponse de module résilient d'agrégats de laitier d'acier en tant que matériaux de construction de route recyclés

Farshid Maghool
Swinburne University of technology, Melbourne, Australia

Arul Arulrajah

Swinburne University of technology, Melbourne, Australia

Suksun Horpibulsuk
Suranaree University of Technology, Nakhon Ratchasima, Thailand

ABSTRACT: Steel slag is an industrial by-product formed in the furnace during the steelmaking process. Electric arc furnace slag (EAFS) and ladle furnace slag (LFS) are the primary by-products of steelmaking from steel scraps. This research evaluates the physical, geotechnical and engineering properties of LFS, EAFS and a blend comprising 50% LFS and 50% EAFS (LFS50+EAFS50) through laboratory testing. Specialized laboratory tests undertaken include California bearing ratio (CBR), unconfined compressive strength (UCS), consolidated drained (CD) triaxial and repeated load triaxial (RLT). The shear strength responses of the steel slags were found to vary with dilatancy induced peak strength for LFS and LFS50+EAFS50 and dilatancy associated strain-hardening behavior for EAFS. Based on the high shear strength parameters and adequate stiffness attained, the steel slags were found to have the potential for usage as construction materials. LFS and LFS50+EAFS50, were well-graded and with high CBR values, which would deem them suitable for roadwork applications such as pavement base. EAFS, however were found to be poorly graded and with lower CBR value, were suitable for less stringent applications such as engineering fill and pipe bedding. The viability of using these by-products as construction material can transform these current waste by-products, particularly LFS, from being stockpiled at steel companies' plant and being used instead as a green alternative construction material.

RÉSUMÉ: Les scories d'acier sont un sous-produit industriel formé dans le four au cours du processus de fabrication de l'acier. Les scories de four à arc électrique (EAFS) et de laitier de poche (LFS) sont les principaux sous-produits de la fabrication de l'acier à partir de chutes d'acier. Cette recherche évalue les propriétés physiques, géotechniques et techniques de LFS, de l'EAFS et d'un mélange comprenant 50% de LFS et 50% de EAFS (LFS50 + EAFS50) au moyen d'essais en laboratoire. Les essais de laboratoire spécialisés entrepris comprennent le coefficient de portance en Californie (CBR), la résistance à la compression non confinée (UCS), le triaxial drainé consolidé (CD) et le triaxial à charge répétée (RLT). Les réponses de résistance au cisaillement des scories d'acier varient avec la résistance maximale induite par la dilatance pour LFS et LFS50 + EAFS50 et le comportement d'écrouissage associé à la dilatance pour EAFS. Sur la base des paramètres de résistance au cisaillement élevés et de la rigidité adéquate atteinte, il a été constaté que les scories d'acier pouvaient être utilisées comme matériaux de construction. LFS et LFS50 + EAFS50 étaient bien classés et avec des valeurs CBR élevées, ce qui les jugerait appropriés pour les travaux routiers tels que la base de la chaussée. Les systèmes EAFS, toutefois, se sont avérés être de mauvaise qualité et avec une valeur CBR inférieure, étaient adaptés à des applications moins strictes telles que le remplissage technique et la pose de tuyaux. La viabilité de l'utilisation de ces sous-produits en tant que matériau de construction peut transformer ces sous-produits de déchets actuels, en particulier l'ÉPA, en passant de ceux-ci à l'usine de la sidérurgie, pour en faire un matériau de construction alternatif écologique.

Keywords: resilient modulus, pavement, electric arc furnace slag, ladle furnace slag

1 INTRODUCTION

Industrial wastes are by-products from steel processing with no long-lasting values, resulting from a manufacturing process. The population growth and infrastructure development in major cities have resulted in a number of issues, namely the high worldwide demand for construction materials, scarcity of natural resources and the vast stockpiles of wastes accumulating at landfills. Access to virgin materials is becoming increasingly difficult and costly, hence the recycling and reuse of waste materials is becoming a popular alternative for governments and key decision makers. In the past decade, the engineering properties of various waste materials have been investigated by various researchers, with the intention of being able to substitute to substitute quarry materials with recycled materials in construction projects (Maghool et al., 2016b). To date, however, some attempts have been made to address the reuse of some types of waste materials in infrastructure projects.

Steel is an essential construction material which is widely in civil engineering infrastructure projects and which can be recycled indefinitely. Almost 1600 million tons (mt) of steel were recycled and reused in 2016 alone (Maghool et al., 2016b), a significant increase from 500 mt in the 1960s. Similar to wastes generated by other industrial processes, steelmaking has its own by-product, termed as slag. The production of one ton of steel generates about 200 kg to 400 kg of slag, depending on the manufacturing technique and type of furnace used. Every year 400 mt of slag is generated around the world (World Steel Association, 2016). In the past decade, significant amounts of slag were successfully utilized as a construction material, mostly in the cement and concrete sectors. There are currently no reuse options for certain types of slags, such as ladle furnace slag (LFS), which is a disposal concern to steelmaking companies and environmentalists due to its high lime content.

There are two main methods for the production of steel; steelmaking in basic oxygen furnaces and scrap-based steel making in electric arc furnaces (Heidrich and Woodhead, 2010). This research focuses on the electric arc furnace by-products, which uses electrical energy, fluxes and 100% steel scrap to produce steel. The electric arc furnace generates two types of slags at various stages of the steelmaking process; electric arc furnace slag (EAFS) and ladle furnace slag (LFS). The refinement of one ton of recycled steel in the electric arc furnace generates around 140 kg of EAFS and roughly 40 kg of LFS (Maghool et al., 2016a).To date, several studies on EAFS have been reported to the use of this by-product, given its aggregates high-quality, durability, skid resistance, cementitious properties, highly permeable and excellent particle interlocking. The EAFS by-product has been previously utilized in asphalt mixing and by the concrete sector (Pasetto and Baldo, 2010, Oluwasola et al., 2015, Dippenaar, 2005). On the contrary, most of the studies on engineering properties of LFS were limited to the use of this by-product as supplementary cementing material, after turning it to powder, due to its high lime content and cementitious characteristics (Manso et al., 2013, Serjun et al., 2013). However, the main drawback of turning LFS to powder and converting it to a useful product, is that this operation (weathering, grinding, etc.) is costly, can quickly damage the fine sieves due to the cementitious properties of LFS and is not entirely an eco-friendly process.

The geo-environmental and fundamental geotechnical properties of LFS and EAFS as unbound roadwork materials was studied by Maghool et al. (Maghool et al., 2016a) and recommended that the use of these by-products as aggregates in roadwork applications causes no harm to the environment. The primary purpose of this paper is to further evaluate the shear strength and stiffness characteristics of LFS, EAFS and their mixture, as this aspect has not been studied previously. The use of industrial wastes in civil applications will result in a sustainable and cost-effective alternative for the waste management of these steel by-products, provided that the engineering properties of these materials are comparable to that of traditional quarry materials. In this research, the shear strength and stiffness properties of these by-products were assessed by conducting specialized tests such as California bearing ratio (CBR), unconfined compressive strength (UCS), consolidated drained (CD) triaxial and repeated load triaxial (RLT) test.

2 MATERIALS AND METHOD

The EAFS and LFS samples for this research were produced by a major steel recycling company located in Melbourne, Australia. EAFS is generated at the beginning of steelmaking process in the electric arc furnace, where the steel scrap is smelted and purified using respectively electricity and fluxes. The high temperature of 1600 °C and lime as a flux help the silicate and phosphorus to be removed from molten steel and shape the EAFS. The red-hot steel then poured to ladle furnace for more processing and finalizing the steel product. At this stage, more lime was added to molten steel to make sure the final product, steel is completely purified. The remaining by-product at the bottom of the ladle furnace is LFS.

Representative samples from various stockpiles in steel manufacturing plant were chosen, mixed, passed through a 20 mm sieve and collected for laboratory experiments. The 50% LFS and 50% EAFS were properly mixed and split in the laboratory to produce the LFS50+EAFS50 mixture. The LFS50+EAFS50 mixtures were prepared with the intention to improve the physical properties (poor gradation and lack of fine fraction) of EAFS and strengthen the structure of LFS with durable aggregates of EAFS by-product.

The suite of engineering tests was conducted in accordance with relevant international standards. These included particle size distribution (AS, 1996), particle density (AS, 2000), pH (AS, 1997), Los Angeles (LA) abrasion (ASTM, 2006b), maximum and minimum dry densities using a vibrating table (ASTM, 2006d), modified compaction (AS, 2003), UCS (ASTM, 2006c), CBR (ASTM, 2007b), CD triaxial (ASTM, 2011) and RLT tests (AASHTO, 2007).

After determining the physical and engineering properties of these by-products, including optimum moisture content (OMC) and maximum dry density (MDD), the specimens for shear strength and stiffness tests were prepared and compacted to the targeted OMC and MDD values. CBR specimens were soaked for four days to simulate the worst condition and then followed by a penetration test (at a rate of 1 mm/min). The UCS, triaxial and RLT specimens were all compacted in a split mold with an internal diameter of 100 mm and final height of 200 mm using a modified Proctor compaction effort to at least 98% of OMC and MDD. An axial load at a rate of 1mm/min was applied to an unconfined cylindrical specimen during the UCS test.

CD triaxial compression tests were undertaken to determine the drained shear strength parameters of specimens, which are similar to the field condition where the specimens have been fully consolidated under normal stresses (ASTM, 2011). The compacted specimen was mounted inside the triaxial chamber with a fully saturated porous disk on top and bottom, covered by a rubber membrane and sealed with a couple of O-rings. The triaxial cell was filled with de-aired water and effective confining pressures of 30kPa, 60kPa, 120kPa and 240kPa were applied to the testing specimen. After a specimen was saturated to at least 96% of B-value and fully consolidated under nominated confining pressure, a slow strain rate of 0.01 mm/min was applied to eliminate any excess pore water pressure build-up throughout the shear phase.

RLT tests were conducted on the slag samples to simulate the traffic loading and to determine the resilient modulus (M_R) of the materials. The compacted specimens were mounted in the RLT cell with a porous disk on top and bottom, then covered by a rubber membrane and sealed with a couple of O-rings. The five stages of confining pressures (from 20.7 kPa to 137.9 kPa) and fifteen loading sequences (three loading at each stage of confining) were applied to each sample during the RLT test. At each stage of loading, 100 repetitions of haversine -shaped load (loading period of 0.1 s and resting time of 0.9 s) were applied to the specimen and the average of recoverable height of specimen (at last five cycles of loading) was recorded according to AASHTO standard for base/subbase materials (AASHTO, 2007).

3 RESULTS AND DISCUSSION

Table 1 presents a summary of engineering characteristics of LFS, EAFS and LFS50+EAFS50. LA abrasion value of all specimens was found to be way below the maximum value of 40, which was specified by the road authorities for base/subbase materials (VicRoads, 1998). The pH value of the samples indicated that all the samples are alkaline by nature. Particle density of all the samples was found to be in the range between 3.4 and 3.6 (Mg/m^3) and higher than that of traditional quarries or other waste materials, such as construction and demolition materials that were reported previously (Arulrajah et al., 2013).

Table 1. Engineering properties of LFS, EAFS and LFS50+EAFS50.

Sample	LFS	EAFS	LFS50+ EAFS50
Silt content (%)	14	0.7	9
Sand content (%)	48	25.8	45.3
Gravel content (%)	38	73.5	45.7
Particle density (Mg/m^3)	3.41	3.56	3.5
pH	12.2	10.6	11.1
LA abrasion loss (%)	31	29	29
UCS (kPa)	185	--	62.3
CBR (%)	160	55	138
M_R (MPa)	231-675	198-714	192-770

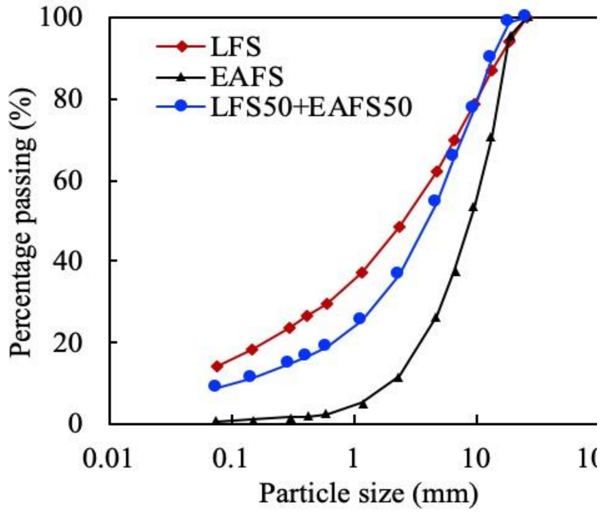

Figure 1. Particle size distribution of LFS, EAFS and LFS50+EAFS50.

Figure 1 shows the gradation curve of the steel slags along with ASTM lower and upper limits. Both LFS and LFS50+EAFS50 met the requirements of ASTM standard (ASTM, 2007a) to be used as type I materials in pavement applications. Further, LFS was classified as having the gradation of a silty sand (SM), EAFS as a well-graded gravel (GW) and LFS50+EAFS50 as poorly graded gravel with silt (GP-GM) in accordance with Unified Soil Classification System (ASTM, 2006a).

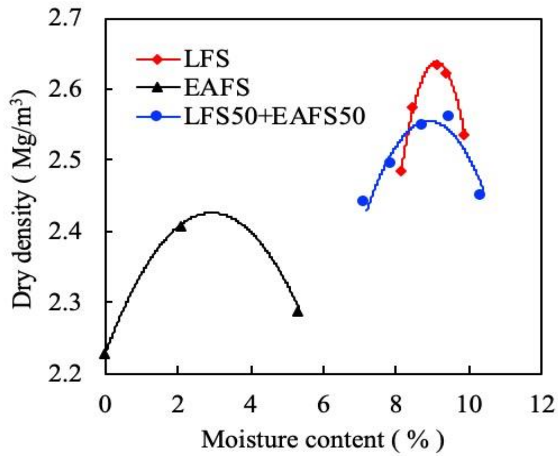

Figure 2. Modified compaction curve of LFS, EAFS and LFS50+EAFS50.

Figure 2 shows the modified compaction curve of the steel slag by-products. The high MDD of the samples was consistent with the result of apparent density test and conformed the high specific gravity values of samples. The UCS test was performed only on LFS and LFS50+EAFS50 specimens, as EAFS specimen cannot be remolded due to the lack of fine and cohesion among its aggregates structure. The average UCS values of LFS were found to be almost three times higher than LFS50+EAFS50, which can be attributed to the high lime content and cementitious nature of LFS. The result of soaked CBR suggested that LFS and LFS50+EAFS50 could be satisfied and met the specified requirement of 80% by local authority for roadwork applications, while the EAFS with the average CBR value of 55% was found to be appropriate for other construction applications such as subbase, engineering and embankment fills.

The shear strength parameters of steel slag aggregates including cohesion (c) and friction angle (φ) were determined using CD triaxial tests. The stress levels of 30, 60, 120 and 240 kPa were used as confining pressures for CD triaxial test. An extra confining pressure of 15 kPa was applied to the EAFS to, further analyze the behavior of this by-product. The shear stress trend of LFS and LFS50/EAFS50 had a well-defined maximum stress and almost constant shear stress value after the maximum shear stress for EAFS. Table 2 presents the result of CD triaxial test.

The friction angle decreased, and cohesion of the specimen increased by the growth of the confining pressure. The cohesion of the specimen was increased from 0.9 kPa (σ'_c = 15-30 kPa) to 69 kPa (σ'_c = 60-120 kPa). The typical cohesion for the loose sample like EAFS should be as low as zero. However, due to the interlocking shape of the sample, this sample will perform as a rock mass in the high confining pressures.

Table 2. Shear strength parameters of LFS, EAFS and LFS50+EAFS50 obtained from CD triaxial test.

Sample	Normal stress range (kPa)	c′ (kPa)	φ′ (degree)
LFS	30-120	84	54°
LFS	60-240	108	52°
EAFS	15-60	0.9	55°
EAFS	30-120	17	50°
EAFS	60-240	69	42°
LFS50+ EAFS50	30-120	75	55°
LFS50+ EAFS50	60-240	142	50°

Figure 3 presents the performance of steel slags under cyclic loading at different confining pressures and RLT test results of which are summarized in Table 1. In contrast to the UCS results, the resilient modulus of LFS was found to be lower than that of EAFS and LFS50+EAFS50.

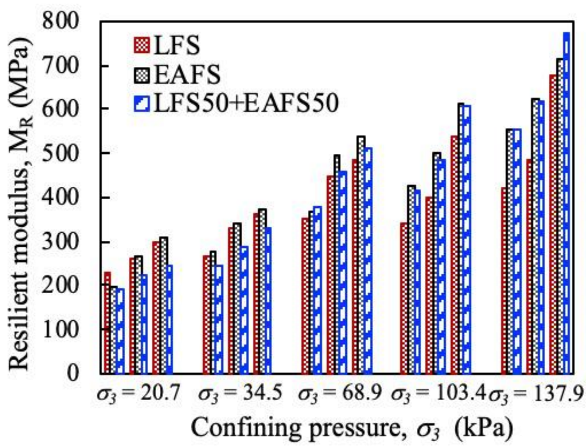

Figure 3. M_R Test results of LFS, EAFS and LFS50+EAFS50.

As apparent in Figure 3, both the EAFS and LFS50+EAFS50 had lower resilient modulus values than the LFS at the commencement of RLT testing due to the flaky particles and cementitious LFS material resisting loads. However, these materials performed better and gained in strength with higher confining pressures and increased in stiffness with higher deviator loading. The RLT test results also indicated that EAFS performed better under higher confining pressure. This can be attributed to the particle shape of EAFS, which can be defined as bulky particles with flakiness index of 6 (5 times less than LFS sample flakiness). Bulky particles (EAFS) had higher single particle crushing value than that of flaky ones (LFS) (Afshar et al., 2016, Mvelase et al., 2017). Similar behavior has been reported on other coarse size waste materials by Puppala et al. (2011) and Rahman et al. (2014).

4 CONCLUSIONS

This study evaluated the shear strength and stiffness properties of LFS, EAFS and their mixture (LFS50+EAFS50) as possible new geo-materials, throughout a range of laboratory testing including CBR, UCS, CD triaxial and RLT tests. The gradation curves of samples indicate that only LFS and LFS50+EAFS50 entirely conform the specified requirements for roadwork applications. The LFS, due to the high lime content and cementitious nature, achieved very high strength and CBR value. EAFS, given its high-quality, durability, skid resistance, cementitious properties, highly permeable and excellent particle interlocking, was found to be a very high-quality but loose aggregate. However, due to the interlocking shape of the sample, this sample will perform as a rock mass in the high confining pressures, which was confirmed by triaxial test results. The LFS50+EAFS50 mixture was prepared to improve the engineering properties of EAFS due to its poor gradation, lack of fine particles, as well as to enhance the strength properties of LFS with durable aggregates of EAFS.

The LFS and LFS50+EAFS50 both had high friction angles similar to other coarse-grained construction materials and very high cohesion due to their cementitious properties. The triaxial result of EAFS were found to be similar to those of a rock mass. The resilient moduli of all steel slags aggregates were found to be higher than those of typical quarry materials. At the beginning of RLT test, both EAFS and LFS50+EAFS50 had lower resilient modulus values than LFS, however, these materials performed better and increased in strength with higher confining pressure and increased in stiffness with higher deviator loading by the end of the test. The RLT test results were consistent with CD triaxial test results and confirmed that EAFS performed better under confining pressure.

LFS and LFS50+EAFS50, were well graded and with high CBR values, which would deem them suitable for roadwork applications. EAFS, however was found to be poorly graded and with relatively lower CBR value and was suitable for less stringent applications such as engineering fill and pipe bedding. The viability of using these by-products as geo- material can transform these current waste by-products, particularly LFS, from being stockpiled at steel companies plant and being used instead as a green alternative material.

5 REFERENCES

AASHTO 2007. Standard method of test for determining the resilient modulus of soils and aggregate materials. AASHTO (American Association of State Highway and Transportation Officials) T 307-99. Washington, DC.

Afshar, T., Mahdimdisfani, Arulrajah, A., Narsilio, G. A. & Emamc, S. 2016. Impact of particle shape on breakage of recycled construction and demolition aggregates. Powder Technology, 308, 1-12.

Arulrajah, A., Piratheepan, J., Disfani, M. M. & Bo, M. W. 2013. Geotechnical and geoenvironmental properties of recycled construction and demolition materials in pavement subbase applications. Journal of Materials in Civil Engineering, 25, 1077-1088.

AS 1996. Methods for sampling and testing aggregates Method 11: Particle size distribution by sieving. Australian Standards AS-1141.11. NSW, Australia: Standards Australia.

AS 1997. Soil chemical tests—Determination of the pH value of a soil—Electrometric method. Australian Standard 1289.4.3.1. Sydney, Australia: Australian standard.

AS 2000. Particle density and water absorption of fine aggregate. Australian Standard 1141.5. Sydney, Australia: Australian Standard.

AS 2003. Soil compaction and density tests - Determination of the dry density/moisture content relation of a soil using modified compactive effort. Australian Standard 1289.5.2.1. Sydney, Australia: Australian Standard.

ASTM 2006a. Standard practice for classification of soils for engineering purposes (Unified Soil Classification System). ASTM standard D2487. ASTM International. West Conshohocken, Pa.

ASTM 2006b. Standard Test Method for Resistance to Degradation of Small-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine. ASTM Standard C131. West Conshohocken, PA: ASTM International.

ASTM 2006c. Standard Test Method for Unconfined Compressive Strength of Cohesive Soil. ASTM Standard D2166. West Conshohocken, PA: ASTM International.

ASTM 2006d. Standard test methods for maximum index density and unit weight of soils using a vibratory table. D4253. West Conshohocken, USA: ASTM International.

ASTM 2007a. Standard Specification for Materials for Soil-Aggregate Subbase, Base, and Surface Courses. ASTM Standard D1241. West Conshohocken, PA: ASTM International.

ASTM 2007b. Standard Test Method for CBR (California Bearing Ratio) of Laboratory-Compacted Soils.ASTM-D1883. Annual Book of ASTM Standards, Vol. 6. 2, ASTM International, West Conshohocken, PA, USA.

ASTM 2011. Standard Test Method for Consolidated Drained Triaxial Compression Test for Soils. ASTM Standard D7181. West Conshohocken, PA.: ASTM International.

Dippenaar, R. 2005. Industrial uses of slag (the use and re-use of iron and steelmaking slags). Maney Online, Maney publishing's online platform, 32, 35-46.

Heidrich, C. & Woodhead, A. 2010. Benchmarking Report for the Sustainability Victoria Business Partnerships Assessment & Benchmarking

Module Wollongong, Australasian (iron and steel) Slag Association.
Maghool, F., Arulrajah, A., Du, Y., Horpibulsuk, S. & Chinkulkijniwat, A. 2016a. Environmental impacts of utilizing waste steel slag aggregatesas recycled road construction materials. Clean Technologies and Environmental Policy.
Maghool, F., Arulrajah, A., Horpibulsuk, S. & Du, Y. 2016b. Laboratory Evaluation of Ladle Furnace Slag in Unbound Pavement Base/Subbase Applications. Journal of Materials in Civil Engineering, 1-9.
Manso, J. M., Ortega-López, V., Polanco, J. A. & Setién, J. S. 2013. The use of ladle furnace slag in soil stabilization. Construction and Building Materials, 40, 126-134.
Mvelase, G. M., Gräbe, P. J. & Anochie-Boateng, J. K. 2017. The use of laser technology to investigate the effect of railway ballast roundness on shear strength. Transportation Geotechnics, 11, 97-106.
Oluwasola, E. A., Hainin, M. R. & Aziz, M. M. A. 2015. Evaluation of asphalt mixtures incorporating electric arc furnace steel slag and copper mine tailings for road construction. Transportation Geotechnics, 2, 47-55.
Pasetto, M. & Baldo, N. 2010. Experimental evaluation of high performance base course and road base asphalt concrete with electric arc furnace steel slags. Journal of Hazardous Materials, 181, 938-948.
Puppala, A. J., Hoyos, L. R. & Potturi, A. K. 2011. Resilient Moduli Response of Moderately Cement-Treated Reclaimed Asphalt Pavement Aggregates. Journal of Materials in Civil Engineering, ASCE, 23, 990 - 998.
Rahman, M. A., Arulrajah, A., Piratheepan, J., Bo, M. W., Asce, M. & Imteaz, M. A. 2014. Resilient Modulus and Permanent Deformation Responses of Geogrid-Reinforced Construction and Demolition Materials. Journal of Materials in Civil Engineering, 26.
Serjun, V. Z., Mirti, B. & Mladenovi, A. 2013. Evaluation of ladle slag as a potential material for building and civil engineering. Materials and technology, 47, 543-550.
VICROADS 1998. Guide to general requirements for unbound pavement materials, Melbourne, VIC, Australia, VicRoads.
World Steel Association, W. 2016. Fact sheet; steel industry by-products. worldsteel.org.