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ORIGINAL PAPER

Physical, microstructure and leaching assessments for pavement road base containing mixed steel slag and cathode ray tube glass

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Abstract
Use of by-product materials, such as steel slag and cathode ray tube glass, as alternative recycled materials in the construction of roads, could reduce the demand for natural aggregates. Measurements of the physical properties (specific gravity, water absorption, Los Angeles abrasion value and soundness) and microstructure characteristics were made to evaluate the effectiveness of using these materials in pavement road base. The laboratory assessments were also conducted using California bearing ratio, unconfined compression strength and indirect tensile strength tests. Leaching tests were performed on six elements (arsenic, barium, cadmium, lead, silver and mercury) to determine the leaching potential of hazardous metals. Element concentration release limits were determined based on the Toxicity Characteristic Leaching Procedure (TCLP). The results indicate that the alternative recycled materials are suitable for use in aggregates and meet the requirements for natural aggregates used for similar purposes. Microstructure analysis shows that the steel slag is more porous and rougher than granite and cathode ray tube glass. The higher percentage of steel slag produces higher California bearing ratio test values for both the soaked and unsoaked samples. Findings from unconfined compression strength and indirect tensile strength tests show that the performance of the mixture was enhanced significantly upon incorporating a higher percentage of steel slag. The samples show a significant strength improvement between 2 and 17%. The concentration of leached barium and lead is higher than that of the other elements, however it is still less than 1% of the TCLP regulatory limit, hence the concentration of the leached elements does not pose an environmental risk. The laboratory test results indicate that mixtures consisting of granite, steel slag and cathode ray tube glass are both environmentally safe and suitable for use as aggregate in pavement road base.

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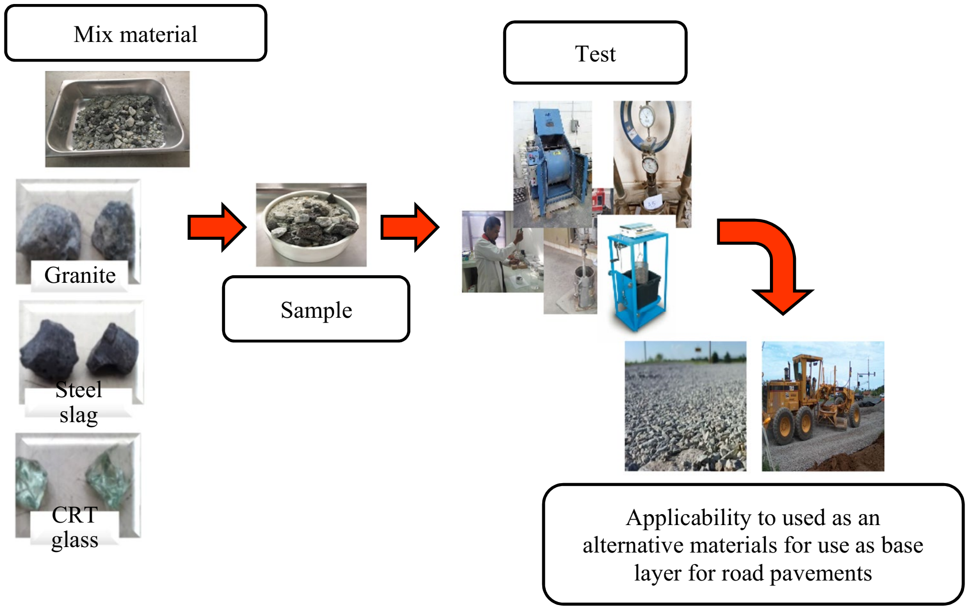
Graphic abstract



Keywords Waste materials · Leaching test · Environmental risk · Road base

Introduction

Over production of waste materials, and their poor management, have a huge environmental impact and can cause serious problems. The environmental, economic and technical problems faced by some countries, in addition to the scarce supply of construction materials, has motivated researchers to recycle industrial waste materials (Aziz et al. 2014). The use of recyclables as alternative materials in the construction of pavement road base has achieved significant development and is becoming increasingly popular in the attempt to minimise environmental impact (Guo et al. 2018).

In various studies and practical implementations, it has been shown that recycled waste can be used as a value adding resource material in construction and in other uses, but it requires careful execution and management to maximise its value. By using recycled materials, the industry would also play its role in the preservation of natural resources, the environment and the ecological system. One of the more effective waste management techniques which should be considered is the reuse of waste materials to ensure environmental health, sustainability and nature friendliness (Jaibee et al., 2015).

The use of waste, or recycled waste, in engineering work contributes positively towards effective resource management (Maghool et al. 2017). However, these efforts must take the environment into consideration to ensure an effective implementation of environmental management (Mohamad et al. 2020; Pauzi et al. 2019). Heavy metals are present in waste materials and there are criteria to determine this (Mombelli et al. 2016). The use of leaching tests is critical to measure the rate at which heavy metals are released into the ecosystem. To ensure that the use of recycled materials is neither detrimental to human health nor leads to environmental degradation, it is important to ensure that contaminants leached from recycled materials do not exceed the permissible limit. It is also important to undertake steps to appropriately and effectively address the problems related to the hazardous materials present in recycled wastes when using them in engineering work, including in subsequent rounds of recycling (Somasundaram et al. 2015).

Environmental risk assessment should include the potential leaching of heavy metals into surface or groundwater. Galvín et al. (2013) pointed out that the seepage of leachate into the soil may cause environmental contamination. However, contamination of the environment is not determined based on how much contaminant (heavy metal elements) is present, but by how much water is seeping into surface water or groundwater (Galvín et al. 2013). Due to concerns about human health and environmental pollution, Mohd Fadzil et al. (2011) assessed the release of potentially toxic metal through leaks or compromised storage of oil sludge. Another factor that determines leaching rate, as stated by the Tiruta-Barna and Geankoplis studies in Law and Evans (2013), is the surface area to volume ratio. It is crucial to carry out assessments with the objective of finding safe and effective methods to use wastes, since this would have a positive impact in ensuring environmental sustainability.

Maghool et al. (2017) attempted to determine the concentration of leached heavy metal elements using the Australian Standard Leaching Procedure (ASLP) method. The leaching test was carried out on a sample of steel slag used as pavement road base and as a filler material. The results of this test were compared against the Environmental Protection Agency (EPA) standard, i.e. the standard set by the Australian authorities. Heavy metal element analysis showed that the use of steel slag aggregate did not pose any environmental risk. The re-use of the optimum amount of steel slag waste ensures minimal use of landfills (Hainin et al. 2015). Environmental assessment was also run-on aggregate samples to determine the concentration of toxic compounds, due to concern regarding possible heavy metal leaching.

Oluwasola et al. (2016) performed a leaching analysis on Electric Arc Furnace (EAF) steel slag and copper mine tailing, both used as asphalt pavement. The results showed that the number of hazardous elements in the materials did not exceed the TCLP regulatory limit. Awazhar et al. (2020) analysed the leaching properties of modified asphalt binder using the synthetic precipitation leaching procedure (SPLP) and found that the concentration of leached heavy metal elements is within the standards for drinking water.

The excessive use of cathode ray tube (CRT) glass, which contains lead and other heavy metals, could have a negative human and environmental health impact. The incorporation of CRT glass in the production of concrete can indirectly prevent these negative impacts. Pauzi et al. (2019) studied how the use of CRT glass substitute for coarse aggregates in cement mixtures affects the environment by conducting a leaching test to determine the concentration of lead (Pb) leached from CRT glass. Uncontrolled release of heavy metal elements into the environment can cause serious problems and can have a harmful effect on human health. Therefore, a careful yet effective technique for the reuse of CRT glass residues will be beneficial to the industry and at the same time, safe for the environment.

This research assesses the environmental risk of using by-product materials, i.e. steel slag, and electronic waste (i.e. CRT glass), as alternative recycled materials. Both materials are used in pavement road base. Optimal use of steel slag and CRT glass can help to reduce the demand for natural aggregates.

Materials

This study uses three types of aggregate, granite, steel slag and CRT glass, in the preparation of the specimen, obtained from the state of Selangor, Malaysia. Granite is used as natural aggregate, while steel slag and CRT glass are used in the specimen as substitute aggregate. The steel slag is categorised as EAF, generated from the melting of scrap produced steel. The CRT glass components were processed by crushing to a size of 4.75 mm or smaller.

Table 1 Gradation limits for road base

BS sieve size (mm)	Percentage passing by weight
20.0	60–90
10.0	40–65
5.0	30–55
2.00	20–40
0.425	10–25
0.075	2–10

Table 2 Mixture sample composition

Mixture sample	Percentage aggregate (%)				
	Coarse aggregate		Fine aggregate		
	Granite	Steel slag	Granite	Steel slag	CRT glass
A1	100	–	100	–	–
A2	70	30	85	–	15
A3	60	40	85	–	15
A4	50	50	85	–	15
A5	30	70	85	–	15
A6	–	100	–	85	15

Sieve analysis was performed to determine the appropriate aggregate size to be used in the mixture for pavement road base. The sieving process was performed to separate the aggregates into samples of various sizes, as specified in the British Standard (BS 1377). The BS grading and limit for 20 mm aggregate for road base gradation are listed in Table 1. To ensure accurate test results, aggregate grading must be performed following the BS recommended limits.

Six mixture samples, with different proportions of recycled materials to replace natural aggregates, were investigated. The composition range covered by the 6 mixture samples enables investigation of the effect of composition on the material properties of the pavement road base layer. Mixture sample composition is shown in Table 2.

Granite, with a maximum nominal size of 20 mm, was used in samples A1 to A5. For sample A1, 100% granite was used for both coarse and fine aggregates and was marked as the control mixture.

In the coarse aggregate mix for samples A2 to A5, the replacement of aggregates was achieved by replacing natural aggregates (granite) with steel slag specimens in different proportions as shown in Table 2. In the fine aggregate mix, the replacement of aggregates was performed between granite natural aggregates and CRT glass specimens, with 15% mix replacement. In sample A6, the coarse aggregate consists of 100% steel slag, while the fine aggregate mix contains 85% and 15% of steel slag and CRT glass, respectively. These samples were used for the California bearing ratio (CBR) and the leaching tests.

Methods

Physical properties

The physical properties of the aggregates were determined using specific gravity, water absorption, Los Angeles abrasion value (LAAV) and soundness tests. For each test, a few representative samples were collected and tested based on the standards set by the American Society for Testing and Materials (ASTM). The specific gravity and absorption of the aggregates were measured as described in ASTM C127 and ASTM C128, respectively. The abrasion resistance of the aggregates was determined based on ASTM C131-81. Soundness testing of the aggregates was carried out as described in ASTM C88. These physical property tests were run to evaluate sample suitability for use in pavement road base.

Microstructure analysis

Microstructure analysis of the sample aggregate, granite, steel slag and CRT glass, was performed using field emission scanning electron microscope (FESEM) and energy-dispersive X-Ray (EDX) techniques. FESEM micrographs, with the intended magnitudes, were performed to determine the shape of the surface particles. One of the parameters that can be evaluated through microstructure analysis is the porosity of aggregates. EDX was used to establish the distribution of granite, steel slag and CRT glass. The Supra 55vp-ZEISS (Merlin-Zeiss, Germany) FESEM equipment was used to examine the microstructure of the sample aggregate.

Before scanning the samples under the FESEM equipment, a thin coat of platinum was applied to the surface using the k550 sputter coater. The sample was then analysed under an electron microscope at a resolution of 15 kV. Following this, the same sample was analysed using EDX to investigate the distribution of the aggregates on the sample surface. EDX was used to make qualitative measurements by analysing the type and percentage concentration of each element in the samples.

California bearing ratio test

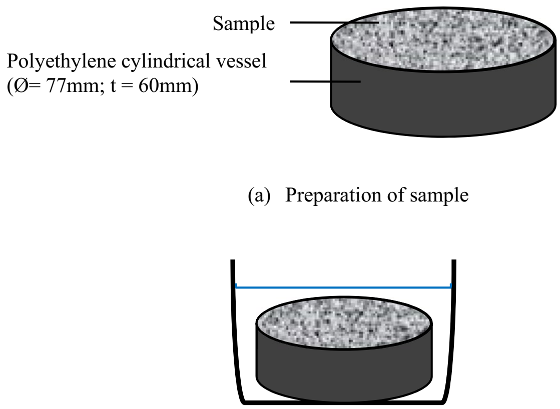
The California bearing ratio (CBR) test was carried out to determine the potential strength of the pavement road base and basic course materials including recycled materials. Samples were compacted using modified proctor compaction at an optimum moisture content (OMC) to obtain a maximum dry density (MDD) of 95%, in accordance with BS 1377: Part 4.

Unconfined compression strength test

Unconfined compression strength (UCS) test is an important parameter in the estimation of the stiffness of pavement material and is used in the design of mechanical pavements. The mixed samples were compacted using a modified compaction method. As with CBR, the samples were placed in five layers. Each layer was compacted by 25 blows of a 4.5 kg hammer. A hydraulic compression strength test machine was used to apply a constant compression rate of 140 kPa/s during the compression strength test, in line with ASTM D1633. The UCS mixture samples were prepared in a metal cylinder mould, measuring 101.60 mm in internal diameter and 116.4 mm in depth. The samples were a blend of aggregate mixtures stabilized with 4% cement (by weight). The samples were cured by placing them in the moulds, kept for 12 h in a moist room, and then removed with a sample extruder. The samples that were removed had plastic wrappings to prevent contact with any water drippings in the moist room, which has a temperature of 25 ^{0}C. The samples were then cured in water for 7 days, in line with the minimum requirement for UCS test. The highest UCS value is identified for use as a design mix. The UCS value is defined as the maximum load divided with the cross-sectional area. The base mixture for the indirect tensile strength (ITS) test was prepared in the similar way to the UCS test to ensure the achievement of a significant value for other performance strength characteristics.

Indirect tensile strength test

Indirect tensile strength (ITS) test is a destructive test used to determine a sample mix's crack resistance. The preparation and compaction of samples for the ITS test are similar to those for UCS. In line with ASTM D1632, the sample mixture was put together in a cylindrical metal specimen mould measuring 101.60 mm in internal diameter and 63.5 mm in depth. Meanwhile, the ITS test procedure, followed ASTM D6931, used the universal testing machine to impose a compression load at a rate of 50 ± 5 mm / min on the samples. The cylindrical samples were placed between two load strips, then loaded for a relatively uniform tensile stress with a compressive load along a diametrical plane and perpendicular to the applied load plane. The procedure went on until the maximum load is reached and the specimen failed.



(a) Preparation of sample

(b) The sample is soaked in the solution with pH of 4.0 ± 0.1

Fig. 1 Preparation of sample for the tank leaching test

Table 3 Conditions of leaching tests

Test conditions	Tank leaching
Liquid to solid ratio (cm^3/g)	1:20
Leaching time (d)	1, 2, 3, 4, 8, 12, 16
pH of leaching solution	4.0 ± 0.1
Temperature (°C)	20 ± 2

Leaching test

Leaching tests were carried out to determine the concentration of leached heavy metals after the samples had been soaked in the leaching fluid. The leaching test is used to evaluate the environmental aspect of a sample, and thus establish its suitability as a road construction material (Pasetto and Baldo 2016). The tank leaching test method is modified from that used in previous studies, Pauzi et al. (2019) and Mohd Fadzil et al. (2011) with reference to measuring the concentration of the leached elements.

The tank leaching test was conducted by compacting a sample of mixture in a cylindrical polyethylene vessel. The specimen was then submerged in the solution liquid. To prepare the leachate sample, 5 ml of the solution (with pH set to 4.0 ± 0.1) for each 100 mm^2 surface area of the specimen was placed in the test chamber. Figure 1 shows how the specimens were soaked in the solution at 20 ± 2 °C at a 24-h interval. At the end of each interval, the leachate is removed, filtered, and analysed for trace elements. The samples were tested for leachate at 1, 2, 3, 4, 8, 12 and 16 days. A 0.45 µm membrane filter was used to filter the leachate, after which the resulting suspended solids were removed. The concentration of leached heavy metals in the leachate was determined using the Inductive Coupled Plasma Mass Spectrometry (ICP-MS) test tool. Table 3 shows the preparation of the leaching test.

Results and discussion

Physical properties

The results for all physical tests are shown in Table 4. All values are within the allowable specification requirement. The following section discusses each test result in detail.

The specific gravities of steel slag, granite and CRT glass are 3.55, 2.68 and 2.54, respectively. Steel slag has the highest specific gravity, followed by granite and CRT glass. The specific gravity for steel slag is 32% higher than that of the natural aggregate (granite). A high specific gravity indicates a stronger aggregate sample (Romero et al. 2013).

The water absorption values are 0.49% for granite, 1.80% for steel slag and 0.19% for CRT glass, all of which fulfil the standard requirement of < 2% and are thus acceptable based on ASTM C127 specifications. The water absorption value is highest for steel slag, compared to granite, followed by CRT glass, which indicates that steel slag has a high porosity and can therefore absorb more water than the other two types of aggregate. According to Arulrajah et al. (2014), high water absorption leads to a bell-shaped compaction curve, a typical characteristic of coarse-grained materials. The use of material with considerable potential has an impact on the construction of road pavement. CRT glass has the lowest water absorption due to its smooth surface and impermeable layer. Pauzi et al. (2019) have shown that the smooth texture of CRT glass makes the concrete mixture more workable. Low water absorption results in a flat compaction curve that is not sensitive to water content and gives a high dry density value. This in turn affects compaction work, where materials with low water absorption require a high compaction energy.

Table 4 Physical properties of aggregate

Test	Test Method	Sample aggregate			Specification Requirements
		Granite	Steel slag	CRT glass	
Specific gravity	ASTM C127	2.68	3.55	2.54	–
Water absorption	ASTM C128	0.49	1.80	0.19	< 2%
LAAV	ASTM C131-81	34.12	21.50	–	< 45
Soundness	ASTM C88	0.20	0.02	–	< 18%

The LAAV test results for granite and steel slag (34.12% for granite and 21.50% for steel slag) indicate that both aggregates fulfil the specification of < 50% stated in ASTM C131-81 for road construction work. The lower LAAV value for steel slag indicates that it has good wear resistance and mechanical properties. This conclusion is supported by other studies, which found steel slag is a suitable aggregate due to its good mechanical properties (Hainin et al. 2015).

The soundness test was carried out on various sizes of coarse aggregate samples. The results showed that granite has the highest soundness, while steel slag has the lowest. Soundness of 0.20 for granite and 0.02 for steel slag are acceptable according to the ASTM C88 specifications of less than 20% for road construction work. Steel slag has higher durability and stability than granite, giving it the ability to resist bad weather conditions, in particular freezing and thawing. The result proved that steel slag has beneficial, stable and good material properties and good soundness, which makes it suitable as the granular base in road construction.

Microstructure analysis

Figure 2 presents FESEM images of granite, steel slag and CRT glass aggregate samples at a magnification of 2.50 K×. The three FESEM images show the distinct surface of each sample. The surface texture of the granite and steel slag aggregates is rough, irregular and uneven, the surface texture of granite being rougher. Oluwasola et al. (2016) observed a similar microstructure in steel slag.

Kosior-Kazberuk and Grzywa (2014) discovered that the rough surface texture of steel slag and granite enables a better internal friction which strengthen the bond between materials in the mixes. Road construction applications that utilise steel slag will enjoy better interlocking and friction, leading to greater stability as well as improved resistance to rutting and skidding as compared to natural materials (Hainin et al. 2015). The surface texture of CRT glass is smoother and irregular. The irregular surface of CRT glass is caused by the crushing of the CRT glass to obtain fine aggregates that are smaller than 4.75 mm. In the study by Pauzi et al. (2019), crushed CRT glass is found to have a smooth texture.

This study uses EDX spectrum to compare the aggregates' elemental composition. As shown in Fig. 3, a high silica (Si) weight percentage can be seen for granite and CRT glass, where Si is 41.3 wt% for granite and 24.2 wt% for CRT glass. The neutralizing pozzolanic properties of

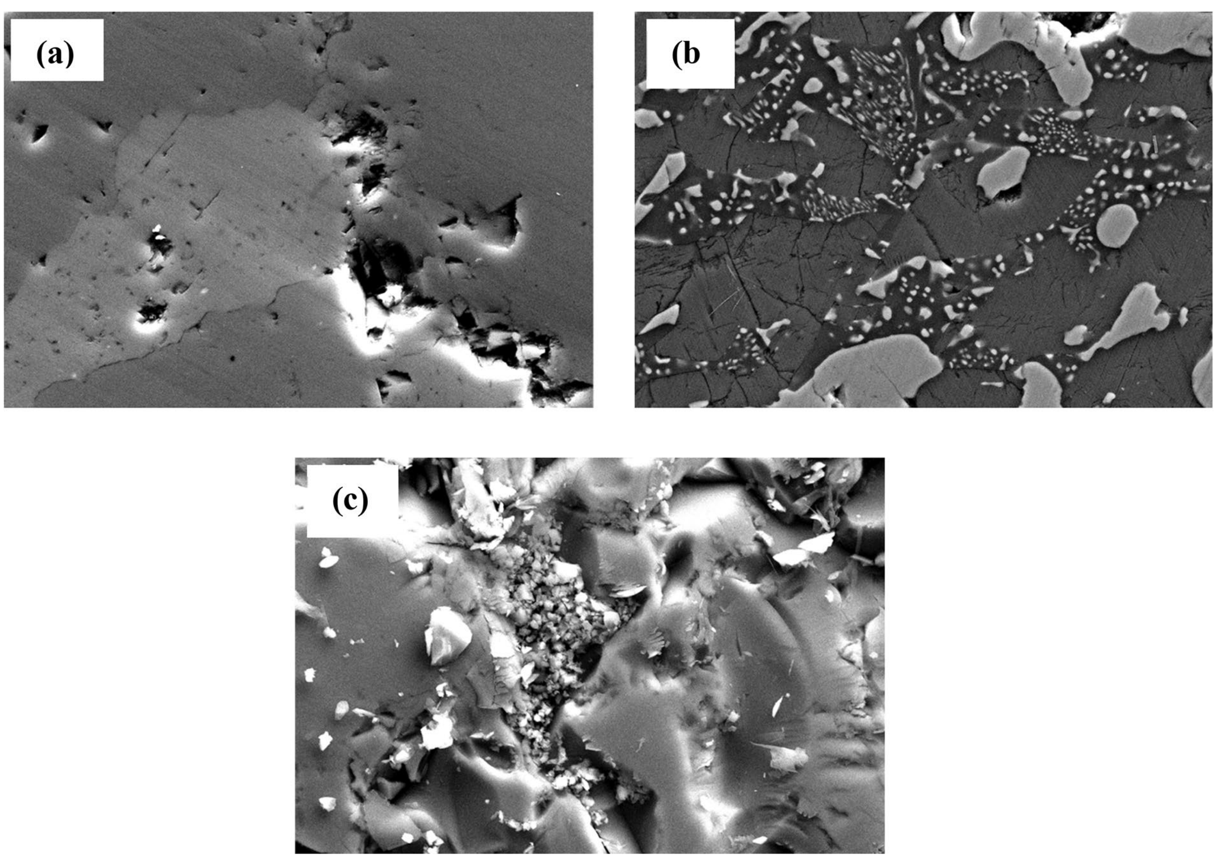


Fig. 2 FESEM image of (**a**) granite, **b** steel slag and **c** CRT glass

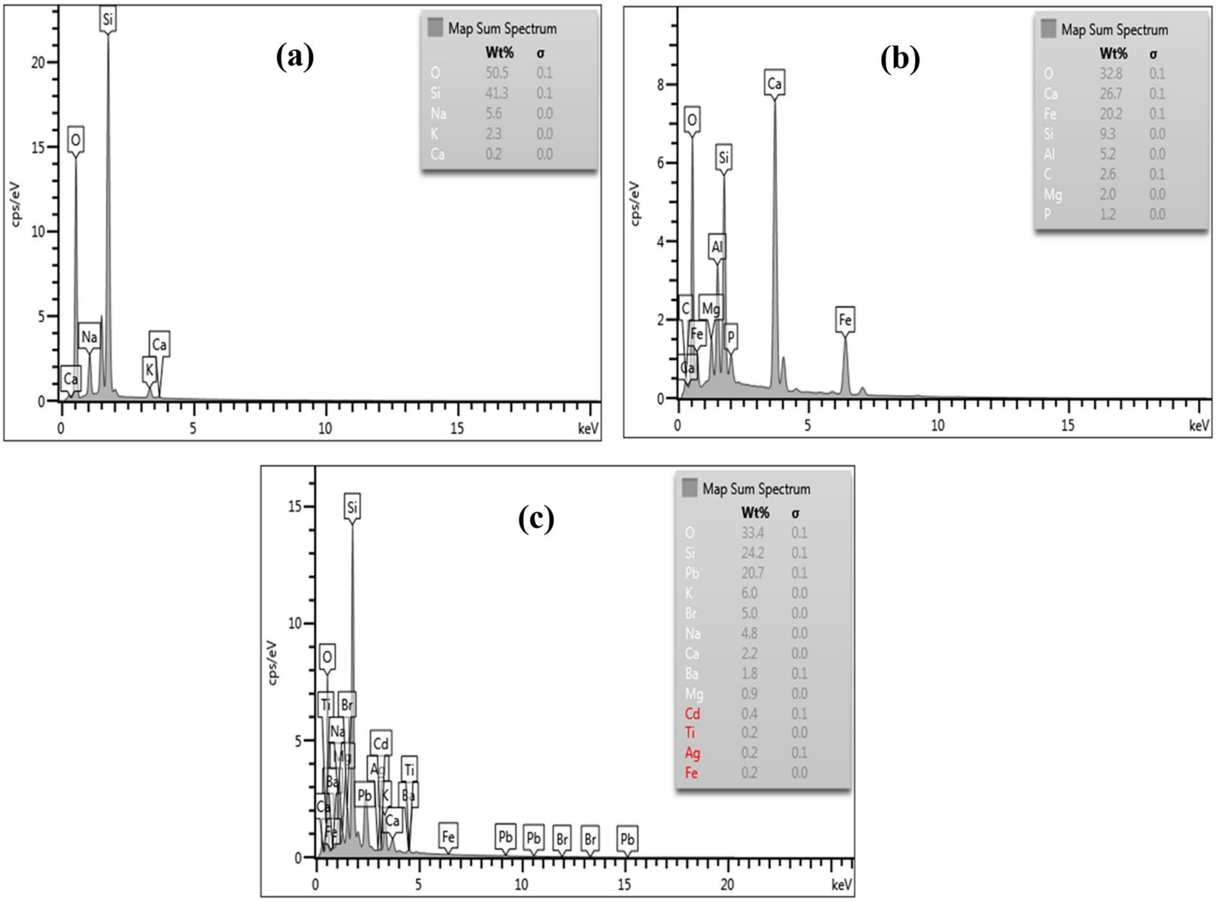


Fig. 3 EDX spectrum of (**a**) granite, **b** steel slag and **c** CRT glass

Si present in these aggregates may affect the strength of a material (Pauzi et al. 2019; Ling and Poon 2014).

CRT glass is high in Si which allows it to be incorporated as a substitute raw material for fine aggregates in various building material products including foam glass, glass ceramic bricks and concrete materials (Yu-Gong et al. 2016). CRT glass can be used as a sustainable material for replacing granite as a fine aggregate, due to its high weight percentage of Si and comparable strength (Pauzi et al. 2019).

High weight percentage constituents in steel slag are calcium oxide (26.7 wt%) and ferum oxide (20.2 wt%). The presence of calcium oxide provides potential cementitious properties (Jiang et al. 2018) and ferum oxide gives high density and hardness (Qasrawi 2012). Generally, the primary chemical compounds of steel slag are CaO, Fe_2O_3, SiO_2, Al_2O_3 and MgO (Yüksel 2017), which make up 88–90% of the steel slag (Aziz et al. 2014). According to Hainin et al. (2015) studies have shown that the presence of magnesia and lime has no effect on steel slag, but that excessive amounts of magnesia and free lime may cause hydration and expansion in a humid environment.

The results of FESEM and EDX analysis showed that granite and steel slag possess a coarse textured surface, which can lead to high skid resistance when both elements are mixed together. The angular shape of granite and steel slag, which leads to good interlocking and high specific gravity, provides the mixture with better stability. One of the benefits of using CRT glass as fine aggregate is that its pozzolanic properties contribute to enhancing the bond among the aggregates. With these properties, steel slag and CRT glass can replace natural aggregates (granite) as both meet the requirements for aggregates used as pavement road base.

CBR analysis

Table 5 shows CBR test results for the samples, both soaked and unsoaked. The highest CBR test values (316.66% and 272.72%, for soaked and unsoaked, respectively) were obtained for sample A5 with the same mixing conditions. However, using 100% steel slag as coarse aggregate in sample A6, significantly reduced the CBR test values (254.62% and 216.49%) for soaked and unsoaked, respectively.

Table 5 CBR test results of mixture sample

Mixture sample	OMC (%)	MDD (Mg/m^3)	CBR (%)	
			soaked	unsoaked
A1	6.40	2.120	146.01	117.62
A2	6.20	2.270	191.74	168.03
A3	6.10	2.330	211.79	196.46
A4	5.90	2.390	239.87	200.98
A5	5.80	2.532	316.66	272.72
A6	5.60	2.900	254.62	216.49

The results of the CBR test show that an increased percentage of steel slag in the mixtures results in an increase in CBR test values of 2 to 50% for the soaked and unsoaked mixtures. Permeability and shear resistance are higher when the aggregates are in a dry state, compared to when the aggregates are in a wet state (Ayan et al. 2014).

UCS analysis

The UCS test was conducted on the sample compacted at optimum moisture contents. The initial stiffness and peak compressive strength values of the samples increased as the amount of waste steel slag increased. Figure 4 shows the variation of UCS values for the sample at different mixture ratios. The UCS test results for optimum compressive strength for 7 days of immersion curing in water equivalent to 5.67 MPa occurred on the A6 sample mixture. The UCS values for other mixes, in descending order, are A5 with values of 4.85 MPa, A4 (4.35 MPa), A3 (4.23 MPa), A2 (3.85 MPa) and control mix, A1 (3.64 MPa). The UCS values showed higher reading strength for all mixed samples compared to the minimum requirement set by the standard, that is 0.70 MPa. The standard value requirement here refers to the JKR standard (JKR 2008). The increase in the steel slag content seems to indicate that the results obtained are influencing the internal stiffness of the mixture. The stiffness strength formed between aggregate mixtures further strengthens the internal strength of the aggregate for better mixture formation. The use of steel slag can improve the stiffness superior to natural aggregates (Yüksel 2017).

ITS analysis

Figure 5 shows the mix design and the performance results for ITS. For all samples, the values of ITS tests increase with higher steel slag content. These results have shown that after 7 days of ageing, mixture A6 has an optimum ITS value of 0.60 MPa. The ITS values for other mixes, in descending order, are A5 with values of 0.51 MPa, A4 (0.46 MPa), A3 (0.44 MPa), A2 (0.42 MPa) and control mix, A1 (0.40 MPa). ITS values for all samples exceeded the minimum values required by the JKR standard, set by 0.20 MPa. The increase in the steel slag content indicate that the results obtained are influencing the internal resistance strength of the mixture. Jeffry et al. (2018) stated that through increasing internal strength resistance, crack resistance also increases. This will help and influence good bonding on the mixture being tested.

Leaching properties

Heavy metals are carcinogenic to humans and can cause chronic degenerative changes, especially increased occurrences of tumours (Abah et al. 2014), and impairment to the human central nervous system (Alissa and Ferns 2011).

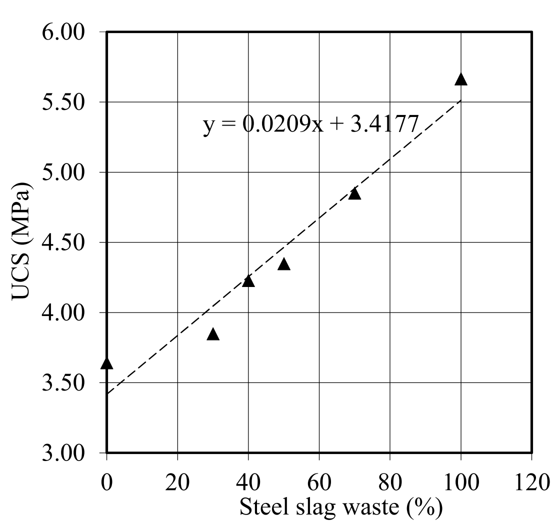


Fig. 4 UCS value with various percentage of steel slag content

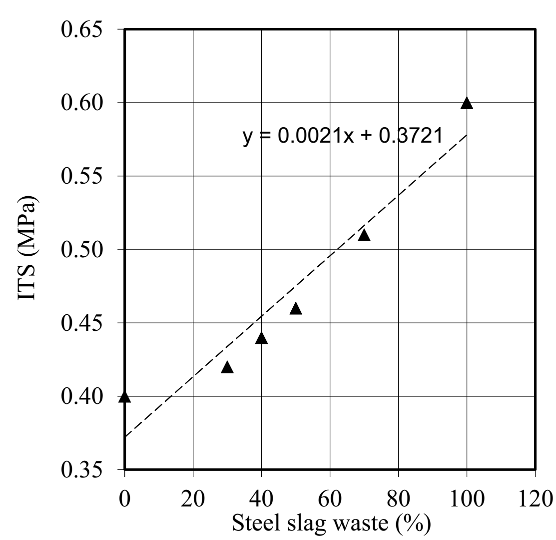


Fig. 5 ITS value with various percentage of steel slag content

Table 6 shows the tank leaching test results for six heavy metal elements, arsenic (As), barium (Ba), cadmium (Cd), lead (Pb), silver (Ag) and mercury (Hg), which are presented as the average cumulative concentration (mg/L) of the elements leached from each mixture sample (A1 to A6).

Arsenic (As) is present in various minerals and is commonly found combined with sulphur, oxygen and iron. It also exists in the form of pure elemental crystals. Granite is an igneous rock which contains arsenic (Chiban et al. 2012). As (Tapio and Grosche 2006) and Cd (Abah et al. 2014) are hazardous and endanger humans and the environment. In humans, exposure to these metals has been shown to cause skin, lung, bladder, kidney, and liver cancer.

Pb that is not properly treated poses a serious risk to human health and the environment. Pb leaching can cause environmental damage due to acidification, through the contamination of soil and the pollution of groundwater (Yu-Gong et al. 2016). Continuous exposure to elemental Hg, especially through inhalation, may cause damage to the internal organs of humans, including impaired kidney function (Alissa and Ferns 2011). The release of Hg into the environment can eventually have a toxic effect on humans (Jaibee et al. 2015).

The leached heavy metal element concentrations were compared with the TCLP regulatory limits. Although the leached concentrations of Ba and Pb are higher than those of the other heavy metal elements, the concentrations of all the six leached heavy metal elements remain within the TCLP regulatory limit.

Figure 6 shows the cumulative concentration release (mg/L) for each heavy metal element per unit area, against the duration of exposure. The leachable behaviour of elements between the different samples varies with the content of the samples. Samples A2 and A3 leached the highest amount of As because granite and steel slag are present, but the amount is within the TCLP regulatory limit. Sulphur and As are present in the granite (Chiban et al. 2012) and steel slag samples, where the As is present in combination with iron and oxygen. However, the presence of sulphur in steel slag does not have any significant impact. Hainin et al. (2015) stated that the percentage of sulphur ranges between

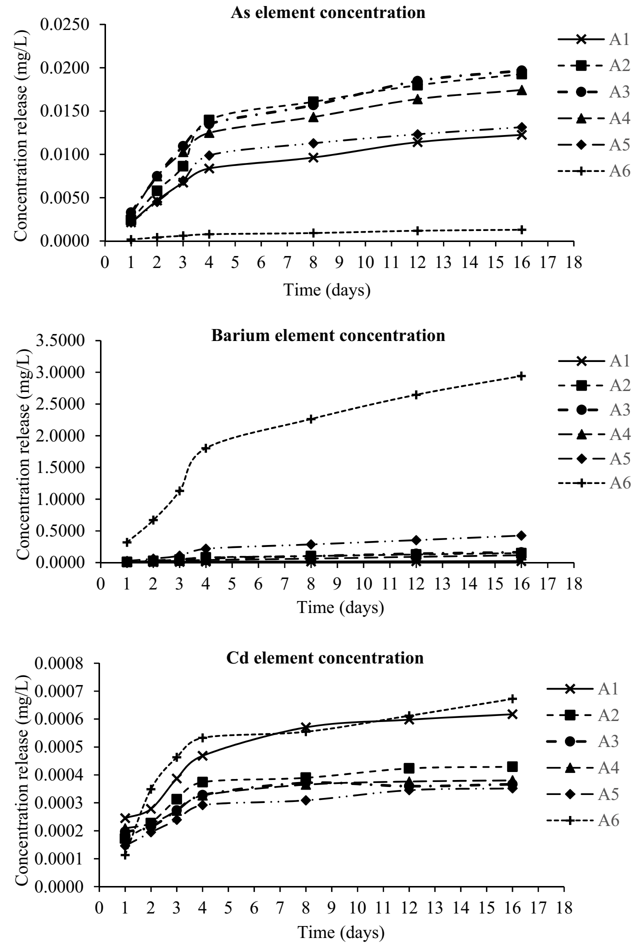


Fig. 6 Cumulative concentration release for each heavy metal element per unit area, against duration of exposure

0 and 2%. Samples A6 and A1 leached the highest concentrations of Ba and Ag, respectively.

A study conducted by Sas et al. (2015) used steel slag as the road sub-base material, and the results of tests for chemical properties showed the concentration of Ba to be the third highest compared to other heavy metal elements; however, still within the permissible range. The results showed that the released concentration of Ba from all samples was very

Table 6 Average cumulative concentration of heavy metals in the leachate

Heavy metal element	Concentration (mg/L)						
	A1	A2	A3	A4	A5	A6	TCLP Limit
As	0.0018	0.0028	0.0028	0.0025	0.0019	0.0002	5.0000
Ba	0.0034	0.0214	0.0233	0.0165	0.0609	0.4204	100.0000
Cd	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	1.0000
Pb	0.0077	0.0088	0.0098	0.0097	0.0115	0.0121	5.0000
Ag	0.0004	0.0002	0.0002	0.0002	0.0002	0.0002	5.0000
Hg	2×10^{-5}	5×10^{-5}	1×10^{-5}	1×10^{-5}	5×10^{-5}	2×10^{-5}	0.2000

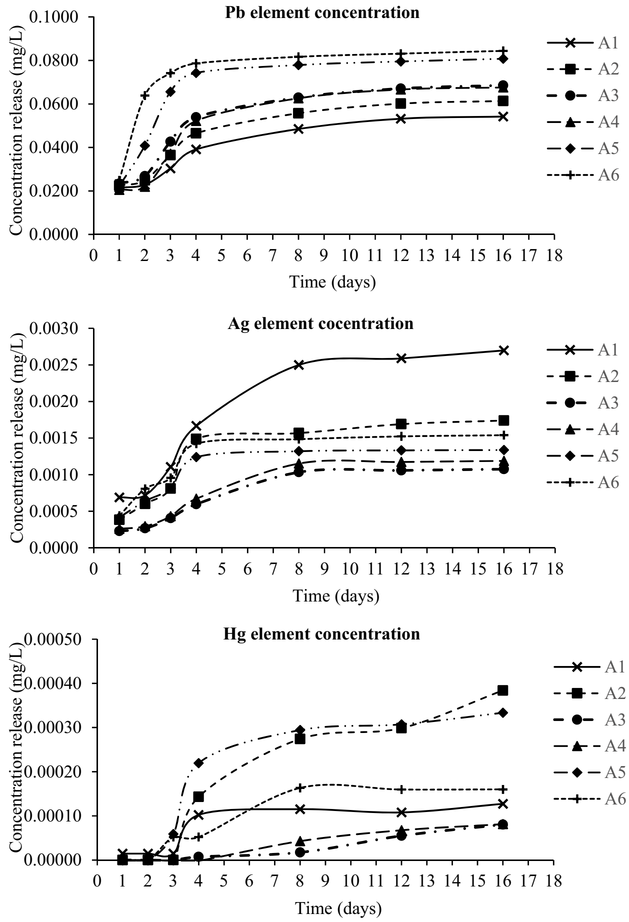


Fig. 6 (continued)

low compared to the TCLP regulatory limit. Pasetto and Baldo (2016) and Sas et al. (2015) asserted that steel slag can be safely used in pavement road base without serious toxic effects.

Compared to the control sample, the concentration of Ag released from all samples decreased with lower percentages of granite in the samples. Occasional exposure to Ag does not have any harmful effect on humans and the environment.

The graph for the concentration release of Cd shows that the cumulative concentration for all samples becomes fairly horizontal. The graph shows an even cumulative concentration plot with increasing duration of exposure. The cumulative concentration of Cd and Hg is very low.

The presence of Pb is caused by CRT glass, and Pb is the main hazardous material content of CRT glass (Nnorom et al. 2011). The incorporation of CRT glass as a replacement for fine aggregates in the samples in this study is controlled and limited to 15%. Arulrajah et al. (2013) proposed that the optimal replacement of recycled glass is up to 15%, with a maximum particle size of 4.75 mm, which is the optimal percentage with regard to the environmental properties for road and footpath applications. The findings in the research by Ling and Poon (2014) show that Pb concentration is within the TCLP regulatory limit when the percentage of CRT glass in the mixture does not exceed 25%. The graph for the release of Pb shows that each sample has a horizontal plot that is evenly spaced up to day 16. This indicates that the amount of Pb released levels off during the immersion period. Moreover, the concentration of Pb is still within the standard limit. Based on the TCLP regulatory limits, all mixtures imply no environmental impact or hazardous risk, and are suitable for use as aggregate in road construction applications.

Conclusion

Several conclusions can be drawn from this study, as follows:

- Physical property test results indicated that both steel slag and CRT glass meet the requirements for aggregates in pavement road base construction and can therefore be used as a replacement in the mixture.
- Microstructure analysis of the aggregate samples showed that steel slag is more porous and rougher than granite and CRT glass. Because of these properties, steel slag interlocks better, has better friction, is more stable, and has greater resistance to rutting and skidding compared to natural aggregates.
- The CBR test indicated that all mixtures meet the minimum 80% requirement of BS 1377: Part 4 standards. The replacement of coarse natural aggregate (granite), with up to 70% steel slag, resulted in higher MDD and CBR. The CBR for both soaked and unsoaked samples increased by 2% to 50%. The substitution of 100% steel slag for the coarse aggregates in the A6 sample resulted in a significant decrease in the CBR, although still within the permissible range.
- The evaluation for the potential of the mixture, measured by the UCS and ITS test, in meeting the minimum requirements according to JKR standards is 0.7 and 0.2 MPa, respectively for 7 days curing period of all mixtures. It was found that the occurrence of an increase of the strength value for each mixture was a significant increase, of between 2 to 17%. The increase in the percentage of steel slag content has affected the resistance yield to the internal strength of the mixture. As a result, this condition has created a strong bond between the aggregate mixtures through a uniform matrix mixture distribution that affects the interlocking properties in the aggregate mixture in question.
- The elements leached under field conditions from the three materials studied in this research, granite, steel slag and CRT glass, are not hazardous to the environment.

The leaching test found that the concentrations of the six heavy metal elements (particularly Pb) were below the TCLP regulatory limit.

- All mixtures do not harm the environment and can be used as aggregates in road construction. The use of eco-friendly recycled materials will positively contribute to environmental sustainability.

These findings suggest that mixtures containing granite, steel slag and CRT glass aggregate are both environmentally safe and suitable to be used as a base layer for road pavement construction.

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Declarations

Conflict of interest They are no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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