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Utilisation of iron ore tailings as aggregates in concrete

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Abstract: Sustainable handling of iron ore tailings is of prime concern to all stakeholders who are into iron ore mining. This study seeks to add value to the tailings by utilising them as a replacement for aggregates in concrete. A concrete mix of grade 40 MPa was prepared in the laboratory with water–cement ratio of 0.5. The concrete were cured for 1, 2, 3, 7, 14 and 28 days. The properties of the concrete such as workability, durability, density, compressive strength and indirect tensile strength were tested. A controlled mix of concrete was also prepared in similar way using conventional materials and the results were compared with the tailings concrete. It was found that the iron ore tailings may be utilised for complete replacement for conventional aggregates in concrete. The iron ore tailings aggregates concrete exhibited a good mechanical strength and even in the case of compressive strength, there was an improvement of 11.56% over conventional aggregates concrete. The indirect tensile strength did not improve against the control mix due high content of fines in the tailings aggregates but showed 4.8% improvement compared with the previous study where the conventional fine aggregates was partially replaced by 20% with iron ore tailings.

Subjects: Civil, Environmental and Geotechnical Engineering; Engineering & Technology; Mining, Mineral & Petroleum Engineering

Keywords: iron ore tailings; concrete; aggregates; compressive strength; indirect tensile strength; slump

1. Introduction

Western Australia (WA) is endowed with a large reserve of iron ore. This has attracted a lot of iron ore mining activities for many years in the state. Iron ore resource is a very significant player of the economy

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The authors are affiliated to the Geo-technical and Geo-environmental research group of Edith Cowan University in the School of Engineering. Our research focus is in sustainability of the environment and quality in building and construction as well as geotechnical engineering. This work is part of the several research works in the focus subject.

PUBLIC INTEREST STATEMENT

This research has highlighted the possibility of introducing alternative and cheaper materials as aggregates for concrete technology. It promotes sustainability in construction by conserving conventional construction materials. It also gives positive impacts in the economy of construction projects. As an additional advantage, it has introduced an economical and environmentally friendly way to manage mine tailings. This has a potential of reducing the burden on mining industries in the management of their mine tailings.

of WA, with an average yearly production of 316 million tonnes which accounts for about 47% of the total value of all resources mined in the state (W. A. Department of Mines & Petroleum, 2009).

The long-time existence of large-scale iron ore mining in Western Australia has resulted in the accumulation of huge quantities of iron ore tailings in the state which needs to be handled, disposed off and monitored properly. It has been reported that in WA, on average, the production of 1 tonne of iron ore results in the generation of 2 tonnes of iron ore tailings (Price, 2004). It can therefore be estimated that about 632 million tonnes of iron ore tailings are generated yearly in WA. This quantity is so huge to the extent that if sustainable handling of these tailings is not found, it could lead to adverse effects on the environment and human health. One of the common environmental problems associated with these tailings is the formation of acid mine drainage which can be a potential source of surface and ground water pollution (Cassiano, Juarez, Pagnussat, Schneider, & Tubino, 2012). These tailings also consume a lot of land that could be used for other purposes, and compromise the good looks of the environment in these areas (Thomas, Damare, & Gupta, 2013; Yellishetty, Karpe, Reddy, Subhash, & Ranjith, 2008). There can be a potential of erosion from these tailings dumps into the environment (Yellishetty, Mudd, & Shukla, 2012). The current practice is that a smaller percentage of these tailings are returned to the mined-out areas as backfills to fill the void created, while majority of them is stockpiled in the environment or returned to a special tailings dam built for storage purposes.

In order to minimise the problems created by the mine tailings, one potential application area to explore is its utilisation in building and construction. This is because there is a greater potential in this sector where recycled waste products could be considered as construction and building materials. An example is the use of these mine tailings as aggregates in concrete (Shetty, Nayak, & Vijayan, 2014; Thomas et al., 2013; Thomas & Gupta, 2013; Yellishetty et al., 2008).

Aggregates make up about 70–80% of a concrete mix (Shetty et al., 2014; Thomas & Gupta, 2013). As the natural granite quarries for aggregates are gradually decreasing, there would be the need for alternative materials to be used as natural aggregates in concrete. If mine tailings are considered as a partial or complete replacement of natural aggregates in concrete, majority of these tailings could be recycled and used sustainably, by turning these mine tailings into useful resource and providing cheaper alternatives in concrete production (Ugama, Ejeh, & Amartey, 2014). This will eliminate the need to mine virgin materials such as concretes aggregates. The scarce resources could be conserved while at the same time providing sustainable solution to the handling of the tailings. This could make it possible for the mining industries concerned to generate extra income to defray their cost of production to maximise profit margin.

The processing activities associated with the iron ore beneficiation is such that it results in the tailings with particle sizes ranging from fine to coarse (Kuranchie, Shukla, & Habibi, 2014a). If these tailings are segregated properly, both fine and coarse aggregates for concrete can be obtained. Therefore, if the iron ore mining companies in WA could incorporate comprehensive utilisation of the tailings in their operation, it could lead to cleaner production and sustainable development in their operation. This could have a potential of reducing both cost and environmental impacts created by these tailings (Haibin & Zhenling, 2010).

The aim of this paper is to study the feasibility of using the iron ore tailings as both fine and coarse aggregates in making concrete. The paper evaluates the technical and environmental characteristics of the concrete with the main concern of recycling and adding economic value to the iron ore tailings to be used as alternative cheaper materials for concrete aggregates.

2. Experimental programme

In this section, the standard process to make concrete was followed. Several tests were conducted to measure physical properties of concrete at different ages and the results were compared with those of normal concrete made using conventional aggregates.

2.1. Materials
For the normal concrete, conventional materials such as sand, cement and granite aggregates were used. For the tailings concrete being studied, iron ore tailings were used together with the cement to make the new concrete.

The iron ore tailings were obtained from Mount Gibson Iron Extension Hill Operations in Perenjori of Western Australia (WA). The particle–size distribution curve of the original tailings as obtained is shown in Figure 1. The size of the tailings range from fines (<75 μm) to coarse (≤ 32 mm). Other physical and chemical properties of the tailings are presented in Tables 1 and 2, respectively (Kuranchie et al., 2014a).

The mine tailings were segregated using various sieve sizes. The particles ranging from 4.75 mm and below were used as fine aggregates while those ranging from 20 mm down to 10 mm were used as coarse aggregates in making the tailings concrete shown in Figure 2(a) and (b). Figure 3 shows the particle–size distribution curves of the tailings aggregates and they conformed to AS 2758.1: 2014 (Standards Australia, 2014a).

Figure 1. Particle–size distribution curve of tailings as received.

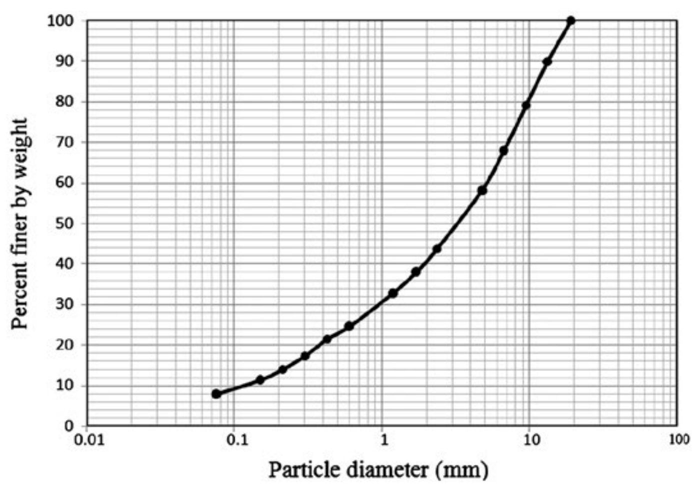


Table 1. Physical properties of iron ore tailings	
Property	**Value**
Fines (clay and silt) (%)	6.5
Sand content (%)	69.5
Gravel content (%)	24.0
Specific gravity	2.65
Minimum dry density, ρ_{dmin} (kg/m^3)	1,685.00
Maximum dry density, ρ_{dmax} (kg/m^3)	1,860.00
Effective grain size, D_{10} (mm)	0.13
D_{60} (mm)	2.67
D_{30} (mm)	0.70
Coefficient of uniformity, C_U	20.54
Coefficient of curvature, C_C	1.41
Soil classification as per USCS	SW-SM (Well graded sand-silty sand)

Source: Kuranchie et al. (2014a).

Table 2. Chemical composition of iron ore mine tailings

Constituents	Amount (%)
CaO	0.03
SiO_2	57.31
Al_2O_3	9.58
Fe_2O_3	25.13
MgO	0.08
SO_3	0.16
Na_2O	0.04
K_2O	0.04
TiO_2	0.61
As	–
Loss on ignition	6.67

Source: Kuranchie et al. (2014a).

Figure 2. Normal and tailings aggregates.

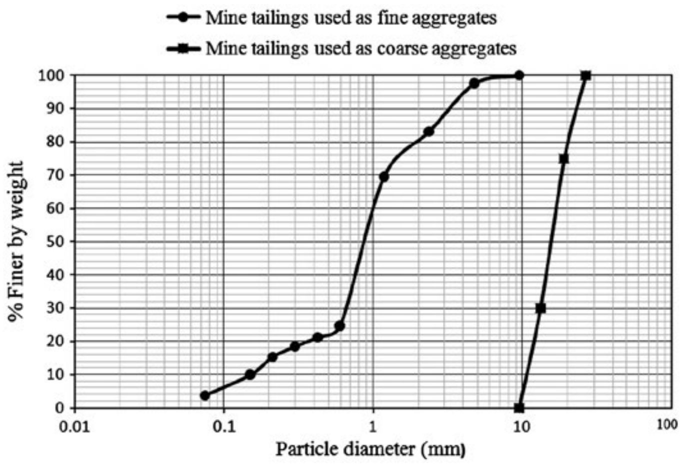
(a) Mine tailings fine aggregates

(b) Mine tailings coarse aggregates

(c) Natural fine sand aggregates

(d) Granite coarse aggregates

Figure 3. Particle–size distribution curves of the tailings used as aggregates.



Ordinary general purpose Portland cement of grade of 43 which conforms to AS 3972 (Standards Australia, 2010) was used. This was obtained from Cockburn Cement Limited in Western Australia. The cement had a normal consistency of 29.5%, soundness of 1 mm with initial setting time of 2 h and final setting time of 3.15 h. The specific gravity of the cement was 3.1.

Commonly used sand for various construction purposes in Perth known as “brickies sand” was obtained from a quarry site, 40 km North of Perth city. This was used as fine aggregates in the normal concrete as a control mix. This can be seen in Figure 2(c). The physical properties of the sand are given in Table 3 (Kuranchie, Shukla, & Habibi, 2014b). The sand was classified as poorly graded sand as per the Unified Soil Classification System (USCS).

Natural granite quarry of sizes 10 and 20 mm, which were obtained from commercial quarry, were mixed and used as the coarse aggregates in the control mix. This is shown in Figure 2(d).

2.2. Mix design and preparation of specimens

A concrete mix design of grade 40 MPa with a water–cement ratio of 0.5 and a mix design ratio of 1:2:3 (cement:fine aggregates:coarse aggregates) was prepared in the laboratory. The mix design recommended by Marsh (1997) was followed and it conforms to AS 1012.2 (Standards Australia, 2014d).

Table 3. Physical properties of sand

Property	Value
Fines (%)	3.85
Sand (%)	96.15
Specific gravity	2.66
Minimum dry density, ρ_{dmin} (kg/m^3)	1,392
Maximum dry density, ρ_{dmax} (kg/m^3)	1,598
Effective grain size, D_{10} (mm)	0.18
D_{60} (mm)	0.38
D_{30} (mm)	0.26
Coefficient of uniformity, C_u	2.11
Coefficient of curvature, C_c	0.99
Soil classification as per USCS	Poorly graded sand (SP)

Source: Kuranchie et al. (2014b).

Ordinary general purpose Portland cement of grade of 43 which conforms to the Standard AS 3972 (Standards Australia, 2010) was used. This was obtained from Cockburn Cement Limited in Western Australia. The cement had a normal consistency of 29.5%, soundness of 1 mm with initial setting time of 2 h and final setting time of 3.15 h. The specific gravity of the cement was 3.1. For the concrete made from the mine tailings, the particle sizes of the mine tailings as described above were used as fine and coarse aggregates.

In the tailings aggregates concrete, i.e. where 100% of the aggregates consisted of iron ore tailings as described above, 18 cylindrical mould specimens of size 100 mm internal diameter and 200 mm length were prepared for 1, 2, 3, 7, 14 and 28 days curing duration for compressive strength test. Other 18 cylindrical moulds of size 150 mm internal diameter and 300 mm length were prepared from the same mix with the same curing duration for the indirect tensile strength test. The mixes were prepared at a controlled indoor temperature range of 25 to 30°C. The process was repeated using conventional aggregates to prepare the control mix which was used for comparison purposes.

After preparation, the small moulds were covered with their lids and plastic sheets were used to cover the big moulds. The specimens were kept in their moulds for 24 h before de-moulding. The specimens were then placed in the concrete curing chamber for the various curing durations explained above. Some quality assessment tests such as the density and the slump tests were performed on the fresh concrete, while after curing, other quality assessment tests on hardened concrete such as compressive and split tensile strength were also conducted.

2.3. Tests for fresh concrete

Density and slump tests were conducted on the fresh concrete for both the control mix and the tailings aggregates mix. Density of both the fresh tailings aggregate concrete and the normal concrete were determined following usual laboratory procedures such that it conformed to AS 1012.5 for determining the density of a fresh concrete (Standards Australia, 1999).

In determining the slump, a standard slump cone with dimensions height 310 mm, lower diameter 100 mm and upper diameter 198 mm was used. The concrete was filled in the cone in three layers. Each layer was compacted using a metal rod for 25 times to ensure good compaction. The concrete was carefully de-moulded from the cone. The cone was then placed upside down close to the concrete and the difference in heights was measured as the slump using a ruler. The procedure according to AS 1012.3.1 was followed (Standards Australia, 2014b). Figure 4 shows the procedure for the slump test.

Figure 4. Determination of the slump of a fresh concrete.

2.4. Tests for hardened concrete

Compressive strength test, indirect tensile strength test and acid resistance and alkalinity test were performed after the concrete have been cured for the various curing duration of the concrete specified. The acid resistance and alkalinity test was limited to the tailings aggregate concrete while all other test were conducted on both the normal aggregate and tailings aggregate concretes. Figures 5(a) and (b) show some examples of how the tailings and the normal aggregates concretes specimens look respectively after they have been cured. The tailings aggregates concretes have a brownish colour and this was due to the brown colour of the iron ore tailings.

Compressive strength was tested for the smaller cylindrical concrete specimens following AS 1012.9 (Standards Australia, 2014c) with a compression testing machine. Three specimens were tested for each curing scheme and the average of the values was used. The compressive strength was calculated by dividing the maximum load (force) observed from the compression machine by the cross-sectional area of the specimen tested and the unit was expressed in megapascals (MPa).

Indirect tensile strength was tested for the beams in the bigger cylindrical moulds. This test was consistent with AS 1012.10 (Standards Australia, 2000). Similarly, three specimens were tested for the indirect tensile strength in each curing duration schemes; 1, 3, 7, 14 and 28 days and the average of the three values was used. The test was done using a compression machine in the laboratory. The indirect tensile strength of the specimen was calculated using the formula

$$T = \frac{2000P}{\pi LD} \tag{1}$$

where T is the indirect tensile strength in MPa, P is the maximum applied load indicated by the compression machine in kN, L is the length of the cylinder in mm and D is the diameter of the specimen.

Mine tailings may contain some sulphide minerals and heavy metals, and there is a possibility that these minerals may come into contact with other oxidising agents such as oxygen and this will lead to the production of some acidic contents (Hitch, Ballantyne, Hindle, & Norman, 2010; Thomas & Gupta, 2013). When the iron ore tailings aggregates concrete are exposed to these extreme conditions, disintegration of the concrete can occur due to acid attack. Also, the ferrous content of the iron ore tailings is subject to corrosion which could also have negative effects on the long-term durability of the concrete. Alkalinity and acid resistance test is therefore a means to check the long-term durability of the tailings concrete against acid attack and corrosion.

In testing for the alkalinity and acid resistance of the concrete, the pH of the resulting solution from the concrete was tested. In doing this, the concrete cubes after the various curing days were dried for 24 h in the oven at a temperature of 105°C. The specimen was cooled down to room temperature and was broken with a hammer to separate the mortar from the concrete. The dried mortar was ground

Figure 5. Tailings and normal aggregates concrete.

(a) Tailings aggregate concretes

(b) Normal aggregate concretes

using a ball mill and sieved to less than 150 μm size. Ten grams of the undersize was then mixed with distilled water and stirred. The pH of the resulting solution was taken using a digital pH meter. If the pH of the resulting solution is above 7, it indicates an alkaline condition which will have the potential of low acid attack. This also indicates that corrosion will be very low. This methodology was recommended by Thomas and Gupta (2013).

3. Results and discussion

The results for the various tests on both fresh and cured concrete have been summarised in this section and it has been discussed in detail. The results include both the normal aggregates and tailings aggregates concrete.

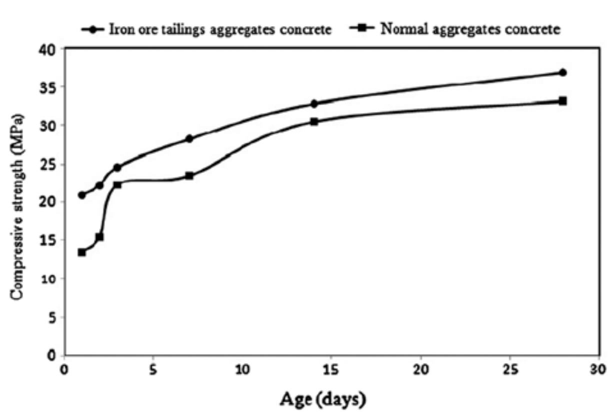
In the absence of experimental results, the density of a fresh concrete may be considered as 2,400 kg/m^3 as a recommended by AS 3600 (Standards Australia, 2009). In this work, the density of the normal concrete is found to be 2,345 kg/m^3 and the density of the tailings concrete is 2,362 kg/m^3. The difference is due to the slightly higher specific gravity of the tailings. The two densities are comparable with those reported in Thomas and Gupta (2013).

Slump test is used to measure the workability and consistency of a fresh concrete (Marsh, 1997). In this work, the slump for the normal concrete was calculated as 80 mm and that of the tailings concrete was 20 mm. Slump ranging from 0 to 25 mm is considered as having low workability.

Compressive strength is the main mechanical property of a concrete that is normally specified in supply of concrete. Figure 6 shows the compressive strength of both normal and tailings aggregates concrete. It was observed that the compressive strength for all the curing ages were higher in iron ore tailings aggregates concrete than in the normal concrete as the control mix. At age of 28 days, the compressive strength of the tailings aggregates concrete was 36.95 MPa while that of the control mix was 33.12 MPa, which shows an improvement of 11.56% of tailings aggregates concrete over normal concrete. This improvement of strength of the iron ore tailings aggregates concrete may be attributed to the chemistry associated with the chemical composition of the iron ore tailings. It has been reported that iron compounds have the potential to accelerate cement hydration (Yellishetty et al., 2008) and this could be the main factor for the improvement of compressive strength observed in the iron ore tailings aggregates concrete which has higher percentage of iron compounds.

Tensile strength of concrete is another crucial mechanical property of concrete. This shows the strength of how the aggregates are bonded to the other materials in the concrete. Concrete structures are susceptible to tensile cracking and it becomes an important factor, especially when the concrete is intended to be used for the design of highway and airfield slabs (Neville, 2012). Therefore,

Figure 6. Compressive strength of normal and tailings aggregate concretes.



the results from the indirect tensile strength test will investigate the influence of the aggregates structure on adhesion and the strength of the bond between the concrete materials.

Figure 7 shows indirect tensile strength of both normal and tailings aggregates concretes for various curing ages from 1 to 28 days. It can be observed that the indirect tensile strength favourably increases with the ageing for both normal (control mix) and tailings aggregates concrete. From Figure 7, it is also observed that tensile strength for one day curing for tailings aggregates concrete was slightly higher than the control mix. As the concrete continues to age, the tensile strength of the normal aggregates concrete became higher than the tailings aggregates concrete. At age 28 days, the control mix achieved indirect tensile strength of 3.36 MPa, while that of the tailings aggregates concrete was 2.82 MPa.

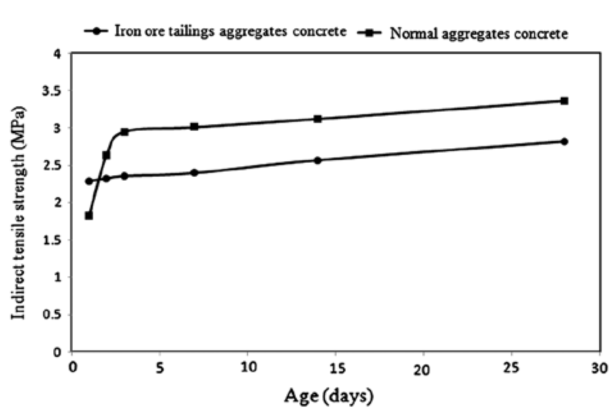
It is noted that while the compressive strength improved, the tensile strength did not improve in the iron ore tailings aggregates concrete as compared with the control mix, although the compressive strength is directly proportional to the tensile strength. The reason may be attributed to the differences in the quantity of fines found in both materials used as fine aggregates. From Tables 1 and 3, it can be seen that iron ore tailings contain 6.5% fines, while the natural sand used in this work contains only 3.85% fines. It should be noted that in this work, 100% of the iron ore tailings were used as fine aggregates in the tailings aggregates concrete. Therefore, this particular concrete will have more fines as compared with the control mix. The higher content of fines in the iron ore tailings aggregates concrete will increase the demand for water in the mix and this will reduce the bond strength existing in the aggregate–cement paste, leading to a reduction in tensile strength (Adedayo & Onitiri, 2012; Ugama et al., 2014). However, the tensile strength exhibited by the iron ore tailings aggregates concrete in this work increased favourably with ageing and there is 4.8% improvement as compared with similar work where only 20% of natural sand fine aggregates were replaced by iron ore tailings as reported earlier by Ugama et al. (2014).

Figure 8 shows the pH values of resulting solution of the iron ore tailings aggregates concrete for the various curing ages. The pH values for the various ages of the concrete ranges from 11.8 to 12.5. These values can be termed as having high alkaline conditions and will, therefore, make acid attack and potential for corrosion very low. This is a good sign of long-term durability of the iron ore tailings concrete.

4. Economic and environmental implication

The cost of managing and monitoring mine tailings is very important to the life of every mine. This is because of some stringent regulations and legislations put in place by the appropriate governmental authorities for the mining companies to adhere to in dealing with their tailings. As part of this, mining companies set aside specific budget for this purpose which is normally included in their cost of production. Comprehensive utilisation of mine tailings in this scenario will provide extra income to

Figure 7. Indirect tensile strength of normal and tailings aggregate concretes.



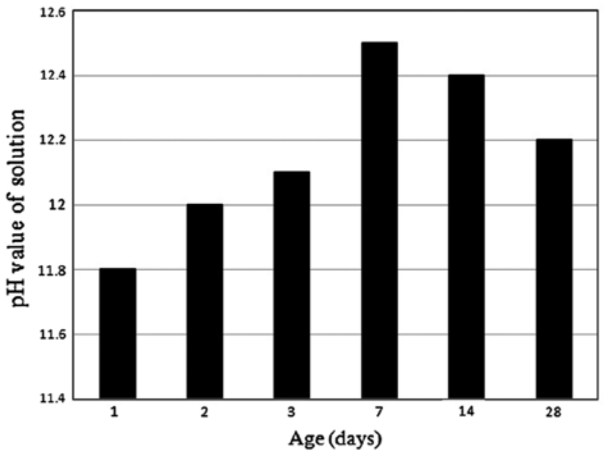


Figure 8. pH values showing the alkalinity of iron ore tailing aggregates concrete.

offset this cost for the mining companies upon mine closure. According to Packey (2012), the incorporation of utilising mine tailings in the operations of the mining companies could reduce rehabilitation costs and minimise the effects of mine closures on mining communities and bring about new economic activity.

Based on the results from this study, and the fact that aggregates forms about 70–80% of concrete, iron ore mine tailings in Western Australia could be considered as aggregates materials for concrete production where huge volumes of iron ore tailings could be utilised. The utilisation of the iron ore tailings could have positive effects on the environment because the quantity of iron ore tailings could be reduced tremendously. This could also lead to the reduction of adverse environmental effects and render the operations of the iron ore mine companies more sustainable in state.

5. Conclusions

This study evaluated the possibility of completely replacing conventional aggregates in concrete with iron ore mine tailings produced in Western Australia to attain the same or better outputs for technical specifications. In the study, both conventional and tailings aggregates were used for comparison. Concrete mix design of 40 MPa and water–cement ratio of 0.5 was used. Based on the results from this study, the following general conclusions could be made:

(1) The compressive strength of the concrete with iron ore tailings aggregates at 28 days was 36.95 MPa which shows an improvement of 11.56% over the concrete with conventional aggregates. This is mainly because of favourable chemical composition of the iron ore tailings.

(2) The split tensile strength exhibited by the concrete with tailings aggregates was 2.82 MPa at 28 days and this is slightly lower than concrete with conventional aggregates by 16% due to higher quantity of fines in the iron ore tailings as compared with the natural sand in the control mix. However, the tensile strength increased favourably with ageing and there was still 4.8% improvement on the tensile strength as compared with similar study reported earlier.

(3) The concrete with tailings aggregates has a low potential of corrosion and a low potential to acid attack due to high pH values of their resulting solution.

(4) The utilisation of iron ore tailings as aggregates in concrete could have positive environmental implications to the mining companies and the mining communities and will provide cheaper alternative materials to bring about economy in concrete production.

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