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# MECHANICAL PROPERTIES OF SELF-COMPACTING GEOPOLYMER CONCRETE CONTAINING SPENT GARNET AS REPLACEMENT FOR FINE AGGREGATE

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## Abstract

Millions of tons of spent garnet, a by-product of surface treatment operations, are disposed of in landfills, oceans, rivers, and quarries, among others every year, thus it causes environmental problems. The main objective of this study is to evaluate spent garnet as a sand replacement in concrete prepared with ground granulated blast furnace slag (GGBS)-based self-compacting geopolymer concrete (SCGC). Concrete mixtures containing 0%, 25%, 50%, 75% and 100% spent garnet as a replacement for river sand were prepared with a constant Liquid/Binder (L/B) mass ratio equal to 0.4. Compressive, flexural and splitting tensile strengths as well as workability tests (slump, L-box, U-box and T50) were conducted on concrete containing spent garnet. As per specification and guidelines for self-compacting concrete (EFNARC) standard, the test results showed that the concrete's workability increased with the increase of spent garnet, while all the other strength values were consistently lower than conventional concrete (SCGC) at all stages of replacement. The results recommended that spent garnet should be used in concrete as a sand replacement up to 25% to reduce environmental problems, costs and the depletion of natural resources.

*Keywords*: Garnet, spent garnet, Geopolymer concrete, self-compacting geopolymer concrete

## Abstrak

Berjuta-juta tan garnet terpakai, produk yang dihasilkan oleh operasi rawatan permukaan, telah dilupuskan setiap tahun di tapak pelupusan, lautan, sungai dan kuari, sekali gus menyebabkan masalah alam sekitar. Objektif utama kajian ini adalah untuk mengkaji garnet terpakai sebagai pengganti pasir di dalam konkrit yang disediakan dengan sanga relau bagas yang digiling (GGBS) berasaskan pemadatan sendiri geopolimer konkrit (SCGC). Campuran konkrit mengandungi 0%, 25%, 50%, 75% dan 100% garnet terpakai sebagai pengganti pasir sungai telah disediakan dengan nisbah cecair/pengikat (L / B) yang tetap bersamaan dengan 0.4. Kekuatan mampatan, lenturan dan kekuatan tegangan, ujian kebolehkerjaan (kericihan, L-box, U-kotak dan T50) telah dijalankan ke atas konkrit yang mengandungi garnet terpakai. Menurut spesifikasi dan garis panduan untuk pemadatan sendiri konkrit (EFNARC), keputusan ujian menunjukkan bahawa kebolehkerjaan konkrit meningkat dengan penggunaan garnet terpakai, manakala semua data kekuatan lain adalah konsisten lebih rendah daripada konvensional (SCGC) pada semua peringkat penggantian. Ia adalah disyorkan bahawa garnet terpakai boleh digunakan di dalam konkrit sebagai pengganti pasir untuk mengurangkan masalah alam sekitar, kos dan kekurangan sumber semula jadi.

*Keywords:* Garnet, garnet terpakai, Geopolimer konkrit, pemadatan sendiri geopolimer konkrit

## 1.0 INTRODUCTION

Currently, the growth in the construction industry and consequent increase in the consumption of natural fine aggregate depletes natural resources [1]. This has increased the consumption of river sand for construction activities, which means that river beds are being over-exploited. This leads to a range of problems that include increased riverbed depth, lower water table, increased salinity and destruction of river embankments [2]. There is a dire and urgent need to explore alternative materials to replace river sand as a fine aggregate in concrete.

Garnet is the general name for a group of complex silicate minerals with similar crystalline structures and diverse chemical compositions [3]. The angular fractures and hardness of garnet, as well as its ability to be recycled, make it desirable for a variety of abrasive purposes. The general chemical formula is $A_3B_2$ $(SiO_4)_3$, where "A" can be calcium, magnesium, ferrous iron or manganese, and "B" can be aluminium, chromium, ferric iron or, rarely, titanium [4]. Garnet occurs worldwide in many rock types, principally in gneisses and schists; other sources include contact metamorphic rocks, crystalline limestones, pegmatites and serpentines. Alluvial garnet is associated with heavy mineral sand and gravel deposits in many parts of the world [5]. Garnet can be reused several times (about 3–5 times). Finally, when the recycled garnet degrades to a point at which it can no longer be reused in the abrasive blasting process, it is removed from the shipyards and named "spent garnet" [6].

Portland cement (PC) is the world's most commonly used binder to produce construction materials. Due to its good mechanical properties, relatively low cost, good durability and availability of raw materials, PC concrete is favoured in many applications [7]. However, the production of PC has some major drawbacks, for example, depletion of natural habitats, production of fossil fuels, utilization of high energy and high emissions of $CO_2$ and other greenhouse gases. Therefore, increasing interest in searching for alternative systems such as geopolymer can be observed [8]. These materials may be beneficial regarding the overall sustainability characteristics by applying industrial by-products as a partial precursor material instead of a primary raw mineral binder like PC. Additionally, depending on the raw materials and alkali activators that are applied, the produced end-products can show better properties compared to PC concrete, such as lower heat of hydration, faster early strength development, stronger aggregate–matrix interface formation, lower thermal conductivity (TC), and higher acid and fire resistance [9–13]. In general, two types of geopolymer materials can be classified: (a) a high calcium system, with ground granulated blast furnace slag (GGBFS) as a typical precursor, with a C-A-S-H type gel as the main reaction product; (b) a low calcium system with Class F fly ash and metakaolin as representative raw materials, with N-A-S-H type gels within a three-dimensional network as the major reaction product [14]. On the other hand, Self-compacting concrete (SCC), which flows under its own weight and does not require any external vibration for compaction, has revolutionized concrete placement. SCC, first introduced in the late 1980s by Japanese researchers, is a highly workable concrete that can flow under its own weight through restricted sections without segregation or bleeding [15]. This concrete should have a relatively low yield value to ensure high flow ability, moderate viscosity to resist segregation and bleeding, and it must maintain its homogeneity during transportation, placing and curing to ensure adequate structural performance and long-term durability. While studies on sand replacements for concrete infrastructures are increasing, there is little or no documentation on spent garnet waste as a construction material product. This necessitates the objective of this investigation, which is to study the engineering properties of concrete that incorporates maximum spent garnet as a replacement of river sand.

## 2.0 METHODOLOGY

### 2.1 Materials and Methods

### *2.1.1 Garnet*

The spent garnet was obtained from a source in Johor, a state located in the southern Peninsular Malaysia. The chemical composition of the spent garnet that has been investigated is shown in Table 1. The spent garnet was kept in an airtight plastic bag and stored in a humidity-controlled chamber. Its physical test data is shown in Table 2 have been prepared by GMA Garnet Pty Ltd by the National Code of Practice for the Preparation of Material Safety Data Sheets 2nd Edition [NOHSC:2011(2003)].

**Table 1** Chemical composition (XRF) of spent garnet

| Chemical composition | percentage % |
|---|---|
| $Fe_2O_3$ | 42.06 |
| $SiO_2$ | 34.76 |
| $Al_2O_3$ | 14.88 |
| CaO | 3.15 |
| MgO | 2.91 |
| MnO | 1.08 |
| $TiO_2$ | 0.78 |
| $K_2O$ | 0.24 |
| $P_2O_5$ | 0.11 |
| ZnO | 0.06 |
| $Cr_2O_3$ | 0.05 |

**Table 2** Physical properties of spent garnet

| Physical properties | Details |
|---|---|
| Appearance | Pink to red color |
| Odor | Odorless |
| PH | Neutral |
| Melting Point | Approximately 1250 |
| Solubility in Water | Insoluble |
| Specific Gravity | 4.1 |
| Hardness | 7.5 – 8.0 Mohs |

The spent garnet was used in a saturated surface dry (SSD) condition to reduce water absorption during mixing process. Spent garnet was sieved through 2.35 mm sieve and retained at 212 μm. Figure 1 shows the sieve analysis results of spent garnet. The upper and lower limits were derived according to ASTM C33-03 Standard Specification for Concrete Aggregates.

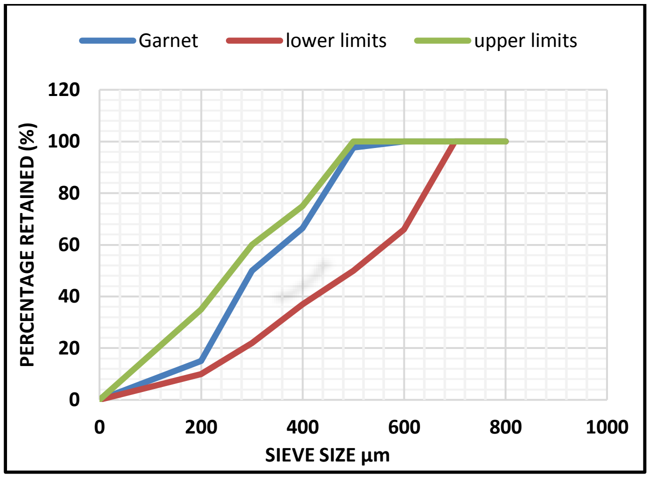

**Figure 1** Sieve analysis results of spent garnet

### *2.1.2 Ground Granulated Blast Furnace Slag (GGBFS)*

The slag was obtained from a source in Johor, a state in the southern part of Malaysia. Slag is commonly used as the source of aluminosilicate to manufacture geopolymer concrete because of its low cost and wide availability. Table 3 shows the chemical composition of slag.

**Table 3** Chemical composition of slag (GGBFS)

| Chemical composition | percentage % |
|---|---|
| $SiO_2$ | 33.80 |
| $Al_2O_3$ | 13.68 |
| $Fe_2O_3$ | 0.4 |
| CaO | 43.2 |
| MgO | 0.46 |
| $K_2O$ | 0.21 |
| LOI | 1.01 |

### *2.1.3 Fine Aggregate*

Locally available sand with a specific gravity of 2.62[16] under SSD condition was used to ensure that water cement ratio is not affected. In this study, sand-replacing percentage with spent garnet was 0%, 25%, 50%, 75% and 100%.

### *2.1.4 Alkaline Liquid*

In general, alkaline liquids are prepared through mixing a sodium hydroxide solution and sodium silicate at room temperature. When the solutions are mixed together, both start to react with each other and a geopolymerization process occurs [17]. The solids must be dissolved in water to yield a solution of the required concentration. The concentration of a sodium hydroxide solution can vary with different molarity. The mass of NaOH solids in a solution varies depending on the concentration of the solution. For example, a NaOH solution with a concentration of 12 molars consists of 12x40 = 480grams of NaOH solids per litre of water, where 40 is the molecular weight of NaOH. This amount of NaOH solids in one litre of water is most of its volume, so it reduces to 361grams for 12 molar concentrations.

### *2.1.5 Superplasticizers (SP)*

The chemical admixture based on Polycarboxylic ether, which is commercially known as Sika Visco Crete-3430, was used in producing SCC as a superplasticizer admixture to increase the workability properties for the mix.

## 2.2 Mixture and Samples Preparation

Table 4 shows the mixture proportions design in accordance with the specifications that meet the requirements of British Standards and EFNARC Guidelines [18]. The cement-free binder was made using GGBFS as one of the resource materials, which is mined in Ipoh (Malaysia). The coarse aggregate used in this study was crushed granite stone with a maximum size of 10 mm and a specific gravity of 2.66 in SSD conditions according to ASTM C33-03 Standard Specification for Concrete Aggregates. In geopolymer synthesis, an alkaline solution plays a major role in the dissolution of silica and alumina from the source material, as well as in the catalysis of the polymerization reaction. A combination of sodium hydroxide and sodium silicate was chosen as an alkaline liquid for this experiment. $Na_2SiO_3$ (Grade A53) was used along with 55.52% water, 29.75% $SiO_2$, and 14.73% $Na_2O$.

NaOH (99% purity, in the form of pellets) was mixed with distilled water to counteract the effects of unknown contaminants in the mixing water. The alkaline activator solution was prepared at least one hour before use.

For all the mixtures, the solution's concentration was kept at 8 M, and to make 1 kg of this solution, 36.1% of pellets were added. 0.3% superplasticizer (Sika Visco Crete-3430) by weight of cement was used to get the required workability for fresh SCGC. 3% SP used was by EFNARC 2002 NOT CLEAR. MODIFY). Tap water was added to the mix according to EFNARC 2002. A total of five mixture samples: TR0, TR1, TR2, TR3, and TR4, were prepared to examine the effects of spent garnet as a replacement for sand on the fresh workability and hardened properties of SCGC. For all the mixtures, the designed spent garnet ratios were 0%, 25%, 50%, 75%, and 100%, while keeping all other test parameters constant. For all the mixtures, the ratio of sodium silicate solution to sodium hydroxide solution by mass was 2.5, whereas the mass ratio of fine aggregates to GGBFS was 2.125. The freshly prepared concrete mixture was then assessed for the essential workability tests required to characterize SCGC. Slump flow, V-funnel, and L-box tests were conducted for this purpose.

## 2.3 Tests

### *2.3.1 Slump Flow Test*

This is the easiest and most commonly used test method for evaluating the flowability of SCGC. Traditional slump cone equipment was used in this test, although the concrete placed in the mould was not tamped. To conduct the test, the slump cone is put onto a rigid and non-absorbent levelled plate, which was filled with concrete without tamping. After filling, the slump cone is put into a vertical position and the concrete is allowed to flow out freely. The diameter of the concrete is measured in two perpendicular directions, and the average of these two measured diameters is calculated. There is no standardized threshold limit for the slump flow value, although, according to the EFNARC guidelines, the SCC is assumed to have good filling ability and consistency if the diameter of the spread lies between 650mm and 800mm. The test was carried out and the results are shown in Table 5 [18].

### *2.3.2 T50cm Slump Flow*

When conducting the slump flow test, the time taken in seconds is recorded from the time when the cone is raised to the time when the flow spread reaches a 500 mm circle. This flow time, which is called the T50 cm slump flow, indicates the relative viscosity and provides a relative assessment of SCC's unconfined flow rate. Less time indicates an increase in flow ability. It should be noted that higher T50 times will be less meaningful and perhaps more variable for more viscous mixes than for mixes with lower T50 times. This test is usually not used as a factor when rejecting batch of SCGC, but as a quality control diagnostic test. The results are shown in Table 5 [18].

### *2.3.3 L-Box Test*

The L-box test is used to assess the filling and passing ability of SCGC. The apparatus consists of an L-shaped rectangular-section box with a vertical and horizontal section separated by a moveable gate, in front of which vertical reinforcement bars are placed. Before starting the test, the L-box is put onto a firm levelled ground and the inside surfaces of the box. Then the vertical section of the box is filled with concrete, the gate separating the vertical and horizontal compartments is lifted, and the concrete flows through the closely spaced reinforcing bars at the bottom and into the horizontal section of the box. When concrete stops flowing, its height at the end of horizontal section (H2) and in vertical section (H1) is measured to calculate the blocking ratio (H2/H1). The results are shown in Table 5 [18].

**Table 4** Mixture proportions design

| Raw Materials in kg/m$^3$ | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Mix no.** | **L/B** | **Slag (kg/m$^3$)** | **Sand (kg/m$^3$)** | **Garnet (kg/m$^3$)** | **Coarse (kg/m$^3$)** | **NaOH (kg/m$^3$)** | **Molarity** | **$Na_2SiO_3$ (kg/m$^3$)** | **SP 3% (kg/m$^3$)** | **Extra. Water 12% (kg/m$^3$)** |
| TR0 | 0.4 | 475 | 950 | 0 | 890 | 58 | 8 | 145 | 15.6 | 62 |
| TR1 | 0.4 | 475 | 713 | 238 | 890 | 58 | 8 | 145 | 15.6 | 62 |
| TR2 | 0.4 | 475 | 475 | 475 | 890 | 58 | 8 | 145 | 15.6 | 62 |
| TR3 | 0.4 | 475 | 238 | 713 | 890 | 58 | 8 | 145 | 15.6 | 62 |
| TR4 | 0.4 | 475 | 0 | 950 | 890 | 58 | 8 | 145 | 15.6 | 62 |

**Table 5** SCGC acceptance criteria according to specification and guidelines for self-compacting concrete EFNAR

| Mix no. | Slump flow (mm) | T50cm slump Flow(sec) | V-funnel (sec) | L-box ratio (h2/h1) | Compressive strength 28 days | Remark as per EFNARC Specification |
|---|---|---|---|---|---|---|
| TR0 | 671 | 5.5 | 12.0 | 0.91 | 79 | Ok |
| TR1 | 675 | 5.0 | 11.5 | 0.92 | 78 | Ok |
| TR2 | 681 | 4.5 | 11.0 | 0.93 | 76 | Ok |
| TR3 | 692 | 4.0 | 7.5 | 0.95 | 75 | Ok |
| TR4 | 700 | 3.5 | 6.5 | 0.97 | 70 | Ok |
| Minimum | 650 | 2 | 6 | 0.8 | Acceptance criteria as per EFNAR | |
| Maximum | 800 | 5 | 12 | 1 | | |

### 2.3.4 V-Funnel Test

This test is mainly used to measure the filling ability (flow ability) of SCGC; it can also be used to evaluate the segregation resistance. The equipment consists of a V-shaped funnel. Approximately 12 kg of concrete is needed to carry out this test. The funnel is totally filled with concrete without compaction or tapping. After the funnel has been filled with concrete, the trapdoor at the bottom is open, and gravity allows the concrete to flow out. The time taken for all the concrete to flow out through the orifice is recorded as the funnel flow time. A funnel flow time between 6 and 12 seconds is generally required for SCGC [18]. The results are shown in Table 5.

## 3.0 RESULTS AND DISCUSSION

### 3.1 Analysis of the Fresh Properties and the Test Results of SCGC

Fresh properties were determined according to slump flow test (slump flow diameter and T50 cm), L-box test, V-funnel test for various mixture compositions and are given in Table 5. Mixture sample TR0 is considered as control sample while TR1, TR2, TR3 and TR4 contained 25%, 50%, 75% and 100% spent garnet, respectively. The test results of quantitative analysis and visual observations indicated that all the concrete mixture samples had the desired fresh properties and were within the EFNARC limits of SCGC [18]. However, the increase in garnet percentage as sand replacement increases the concrete flow and enhances the workability properties because garnet contains more fine particles than the natural sand.

### 3.2 Compressive Strength

The compressive strength test values for the control and spent garnet concrete mixtures are shown in Figure 2. The test data showed that the compressive strength of spent garnet concrete were lower than the control samples during all curing periods. The percentage decrease in the compressive strength relative to control after 28 days was -2.04%, -4.41%, -5.50%, and -11.92% for TR1, TR2, TR3, and TR4, respectively. This shows a decrease in compressive strength could be partly attributed to the fine particles of the spent garnet, which lack appropriate gradient and shape, and thus cannot fill the pore and optimize the pore structure. However, the rough and angular texture of the spent garnet materials increases the bond between the slag and aggregate interface, thus resulting in high strength [19]. It is worth noting that the strength of geopolymer concrete with spent garnet decreased as its percentage increased. In this study, the replacement of natural sand with spent garnet by up to 100% is favourable for making geopolymer concrete without having any effect on the strength criteria. SCGC specimens cast with a 25% spent garnet replacement for natural sand yielded the highest strength throughout the curing period and are considered to be the optimum mixture.

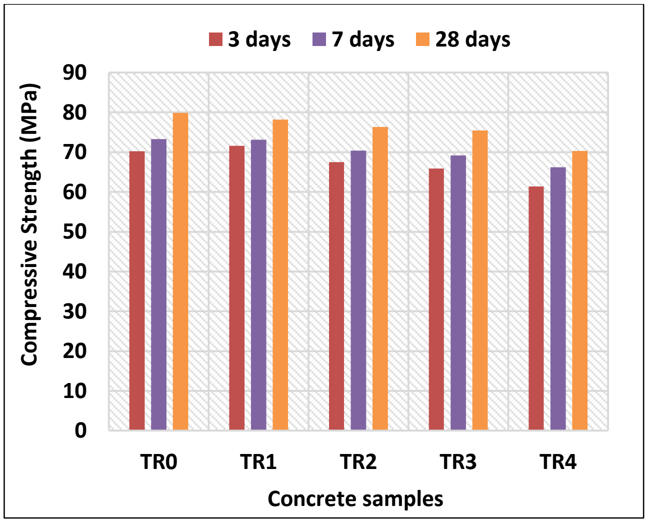

**Figure 2** Compressive strength vs. curing time

### 3.3 Splitting Tensile Strength

Figure 3 shows the splitting tensile strength results. Results indicated that splitting tensile strength of the geopolymer concrete with spent garnet decreased as its percentage increased. The tensile strength decreased after both 7 and 28 days of curing.

However, on when comparing the results after 7 and 28 days, there was a significant decline in the splitting tensile strength of the spent garnet geopolymer concrete mixtures.

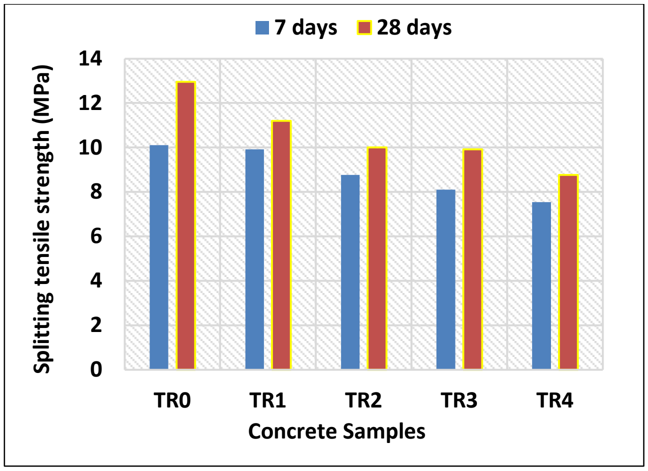

**Figure 3** Splitting tensile strength vs. curing time

The results of the splitting tensile strength of geopolymer concrete after 28 days were -13.51%, -22.78%, -23.47%, and -32.28% for TR1, TR2, TR3, and TR4, respectively. These values were lower than the control mixture. The decrease in tensile strength observed in the spent garnet geopolymer concrete could be due to the weak bonding between the spent garnet particles and the binder paste engendered by the smaller particles of the garnet [20].

### 3.4 Flexural Strength

Flexural strength is the ability to resist an applied bending force such as encountered by concrete pavements or other slabs on ground. A determination of flexural strength is frequently necessary as part of concrete design mixtures to check compliance with established specifications or to provide information necessary to the design of an engineering structure. Flexural test was conducted at room temperature as specified in ASTM D790. The results for flexural strength at 7 days were found to be 1.26 N/mm$^2$, 1.22N/mm$^2$, 0.98 N/mm$^{2,}$ 0.92 N/mm$^2$, 0.89 N/mm$^2$. The outcomes of 28 days' test were 1.50N/mm$^2$, 1.35N/mm$^2$, 1.20N/mm$^2$, 1.11N/mm$^2$, and 0.98N/mm$^2$ for TR0, TR1, TR2, TR3, and TR4, respectively. It can be concluded that flexural strength obtained for spent garnet samples were lower for both 7 and 28 days in comparison to control samples of geopolymer concrete as shown in Figure 4. It could be due to the decrease in sand ratio which leads to lower interlock between fine aggregate and binder [21].

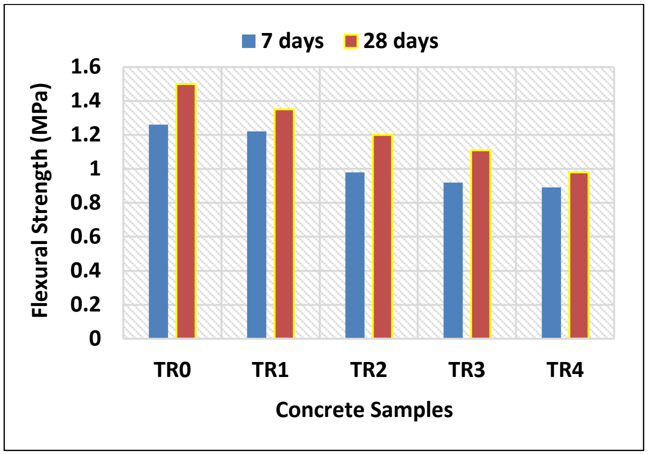

**Figure 4** Flexural Strength vs. curing time

## 4.0 CONCLUSIONS

Control and spent garnet self-compacting geopolymer concrete mixtures had a satisfactory performance in the fresh properties state. The GGBFS can be used to produce geopolymeric binder phase that can bind the aggregate systems consisting of sand, spent garnet and coarse aggregate to form SCGC. Therefore, these concretes can be considered as eco-friendly materials. The outcomes of mechanical properties (compressive, split and flexure) had indicated significant performance for spent garnet series. However, the increase in sand replacement levels by garnet has caused a decrease in strength. Only 25% replacement of sand by spent garnet could be considered optimum for both flow ability as well as mechanical properties.

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## References

[1] Temuujin, J., van Riessen, A., MacKenzie, K. J. D. 2010, Preparation and Characterisation of Fly Ash Based Geopolymer Mortars. *Construction and Building Materials.* 24: 1906-1910.

[2] Gourley, J. T. 2003. Geopolymers, Opportunities for Environmentally Friendly Construction Materials. *Materials 2003 Conference: Adaptive Materials for a Modern Society, Sydney.*

[3] A. Castel, T. Vidal, R. François 2010. Bond and Cracking Properties of Self-Consolidating Concrete. *Constr. Build. Mater.* 24: 1222-1231.

[4] Banno, S., Matsui. 1965, Eelogite Types and Partition of Mg, Fe, and ~Ln between Elinopyroxene and Garnet. *Japan Acad. Proe.* 41: 716-721.

[5] Harris, Paul. 2000. At the Cutting Edge—Abrasives & Their Markets: Industrial Minerals. 388(January): 19-27.

[6] Gorrill, Lindsay. 2003. Global Garnet Market Review: Mineral Price Watch. 97(January): 7-10.

[7] Roskill Information Services Ltd. 2000. The Economics of Garnet. 3d Ed. London, United Kingdom, Roskill Information Services Ltd. 88.

[8] Abrasives. Ch. 1973. United States Mineral Resources. Professional Paper 820.

[9] Davidovits, Joseph. 1991. Geopolymers. *Journal of Thermal Analysis.* 37(8): 1633-1656.

[10] T. S. Ng, Y. L. Voo, S. J. Foster. 2012. Sustainability with Ultrahigh-Performance and Geopolymer Concrete Construction, Innovative Materials and Techniques in Concrete Construction. In: M. N. Fardis (Ed.). ACES Workshop. Springer, Dordrecht. 81-100.

[11] J. L. Provis, J. S. J. van Deventer. 2009. *Geopolymers: Structures, Processing, Properties, and Industrial Applications.* Woodhead Publishing Limited, Cambridge.

[12] N. A. Lloyd, B. V. Rangan. 2010. Geopolymer Concrete with Fly Ash. *2nd International Conference on Sustainable Construction Materials and Technologies*. 1493-1504.

[13] M. Sofi, J. S. J. van Deventer, P. A. Mendis. 2007. Bond Performance of Reinforcing Bars in Inorganic Polymer Concretes (IPCS). *J. Mater. Sci*. 42: 3107-3116.

[14] P. K. Sarker. 2001. Bond Strength of Reinforcing Steel Embedded In Fly Ash-Based Geopolymer Concrete. *Mater. Struct*. 44-1021-1030.

[15] A. Castel, T. Vidal, R. François. 2010. Bond and Cracking Properties of Self-Consolidating Concrete. *Constr. Build. Mater.* 24-1222-1231.

[16] Siddiqui, K. S. 2007. Strength And Durability Of Low–Calcium Fly-Ash Based Geopolymer Concrete. Final Year Honors Dissertation. The University of Western Australia, Perth.

[17] G. Kovalchuk, A. Fernandez-Jimenez, A. Palomo. 2007. Alkali-Activated Fly Ash: Effect of Thermal Curing Conditions on Mechanical And Microstructural Development—Part II. *Fuel*. 86: 315-322.

[18] EFNARC. 2002. Specification and Guidelines for Self-Compacting Concrete. UK. 32.

[19] S. Goyal, K. Singh, A. Hussain, P. R. Singh. 2015, Study on Partial Replacement of Sand with Iron Ore Tailing on Compressive Strength of Concrete. *Int. J. Res. Eng. Adv. Technol*. 3(2).

[20] G. D. Zhang, X. Z. Zhang, Z. H. Zhou, X. Cheng. 2013, Preparation and Properties of Concrete Containing Iron Tailings/Manufactured Sand as Fine Aggregate. *Adv. Mater. Res*. 838-841, 152-155.

[21] Rans, C. D., Alderliesten R. and Benedictus, R. 2011. Misinterpreting the Results: How Similitude Can Improve Our Understanding of Fatigue Delamination Growth. *Composite Science and Technology*. 71: 230-238.