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A Review: Study on Spent Garnet as Construction Material

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Abstract: Numerous environmental problems are mitigated by natural resource depletion, with yearly global use of nearly 25 billion tonnes, including aggregates. Fast industrial growth has witnessed the ever-increasing exploitation of sand from rivers for various construction resolves, which caused an over-exploitation of rivers' beds and disturbed the eco-system. This problem is also related to the amount of waste produced each year. The volume of waste is estimated to rise, reducing available space, and causing pollution. Many studies have discovered inventions and ideas to deal with this situation. Some researchers use the spent garnet in a concrete mix as a partial fine aggregate replacement. The alternative in a concrete mix depends on the properties of the spent garnet that is used and its appropriateness. In this paper, a critical review of spent garnet was discussed in detail to enhance the understanding of this topic.

Keywords: Spent garnet, waste, sand replacement

1. Introduction

Many environmental problems are mitigated by the scarcity of natural resources with annual global use of almost 25 billion tonnes, including aggregates [1]. Rapid industrial growth has witnessed the ever-increasing utilization of sand from rivers for various construction purposes [2], which caused an over-exploitation of rivers' beds and disturbed the eco-system [3]. 'Sand mining' is activity carry out sand extraction from a different environment, for example, inland dunes, beaches and dredged from riverbeds [4]. Natural sand is one of the industrial construction raw materials which play a crucial part within the rivers. It has been mined for use as infill in concrete. Nowadays, river sand mining activity is widely spread all over developing and developed countries. The sand extraction activity for the construction field is the largest industry among the different types of mining activity in both quantity and value [5].

Garnet is a type of sand that is normally used for water jet cutting, sandblasting, and other usages as shown in Fig.1. It can be reused about 3-5 times only. After that, its performance will degrade to a lower level and cannot be reused again in the abrasive blasting process. During that time, it will be removed and called as "spent garnet" [6]. During the process, spent garnet sand is generated as a by-product. It is categorized as solid waste and dumped in the landfill, raising environmental issues. The total utilization of industrial garnet worldwide was estimated as 440k tons in 2002 [7]. The statistics from Malaysia Marine and Heavy Engineering Sdn. Bhd. (MMHE) shown that there were 2000 tons of garnet being imported by this company from Australia to Malaysia within the year 2013 [8]. Success in utilizing the spent garnet would lessen the consumption of natural resources, moreover, ensuring the preservation of the environment for the next generation.

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Fig. 1 - Waste garnet in landfill area

The mineral garnet is commonly found in metamorphic and, to a lesser extent, igneous rocks. Garnet commonly can be found in metamorphic rocks, which are formed through subjected to high temperature and pressure forces within the Earth, such as mica schist, marble, and skarns. At the same time, granite is the igneous rock where garnet forms and exists. Garnet can be extracted by open-pit mining method on the ground. It is then will be removed from the surrounding rock, and followed by the process of washing, screening, and quality sorting for using purposes [9].

Concrete generally is a manmade product in the form of a composite material. It consists essentially of four main basic mixed component materials such as cement, water, fine and coarse aggregates. The cement and water acts as a binding medium, which are embedded particles or fragments of aggregate, normally a combination of fine and coarse aggregate. As concrete is a composite material, the strength of concrete largely depends on the properties of its components in terms of strength, deformation, and adhesion between paste and aggregate [10].

Mix design for a normal cement is basic and easy while satisfying all the required properties for the minimum cost. It is generally composites of cement, fine aggregates, and coarse aggregate and mixed with water as well. In the absolute volume of concrete, the range of cement and aggregates is normally between 7% and 15% and 60% and 75%, respectively. In contrast, the other components include water about 14% to 21%, and air up to 8% [11].

Aggregate as constituent material in concrete includes crushed stone, gravel, sand, and iron-blast furnace slag. The aggregates are necessary to be well graded through a set of sieves with progressively smaller mesh sizes. The aggregate can be categorized into two groups which are fine aggregate and coarse aggregate. For fine aggregate or sand, it passes through sieve No.4, which is 4.75 mm openings. While the other aggregates are retained on sieve No. 4 and above, they are conventionally referred to as coarse aggregate, gravel, or stone [12]. The step of carefully grading the aggregates is essential to select an optimal particle size distribution. In a well-graded aggregate, a maximum packing density is obtained where voids between the coarse aggregates are fully filled by fine aggregates and paste. The high-density packing in concrete is beneficial in the reduction of cement amount needed and subsequently leads to enhance the mechanical and durability properties of concrete. The characteristics of concrete largely depend on the properties of aggregate since aggregate constitutes typically occupy 75% or above of the concrete volume. In order to achieve a good quality of concrete, the properties of aggregates have to be strong and durable.

Aggregates also act as a vital role to contribute strength to concrete. Thus, well-graded aggregates and mix proportion will create a good performance concrete as desired. Aggregates are required to be free from impurities such as organic matter, silts, and oils. This is because any of these impurities may slow down or prevent the hydration reaction between the cement paste and the aggregate particles. Normally, the specific gravity of concrete is 2.4 g/cm3. The density of concrete varies with the amount and density of its constituents. Conventional concrete generally has a density of about 2200 to 2400 kg/m3, which is commonly used in pavements, buildings, and other structures [11].

Nowadays, focus is on waste management efforts for environmentally sustainable growth due to the rising cost of disposal as well as increasing public awareness of the environmental impact. This situation drives the researchers to find an alternative way to replace cement and aggregates by using solid waste. Many waste materials are studied as an alternative material in concrete, including carpet, ceramic recycled aggregates, recycled drill cuttings, plastics waste, palm oil fuel ash, polypropylene tapestry fiber, fly ash. These thoughtful ideas and discoveries minimized the waste piled in dumping areas or disposed traditionally by disposing the inert components on roads and dams. In the case of spent garnet, research on the potential of this material in construction activity which avails in the early of this century is still in the early stage as compared to other waste materials such as fly ash, ground granulated blast furnace slag, crumb rubber and others that has been explored for its use for many purposes since long ago. Up to now, the possible use of spent garnet as partial fine aggregate replacement in asphalt pavement and concrete material has been revealed.

In this paper, spent garnet (refer Fig. 2) is studied as an alternative construction material replacement to fine aggregate, which is sand in concrete. This helps in maximizing the utilization of spent garnet since the spent garnet is designated as a waste product when reaching its maximum number of reusing. Thus, a high amount of it is dumped, leading to worse waste pollution. As sand is replaced by spent garnet, this beneficially improving the environment by reducing exploitation of natural resources and minimizing waste production, and thus maintaining the healthy ecosystem. Other than this advantage, in few previous researches, they found that spent garnet has the potential in enhancing the performance in normal concrete and be a favorable replacement material for the sustainable development of concrete. Nevertheless, the behavior of spent garnet as sand replacement in concrete is still a new discovery that needs further study.

Fig. 2 - Appearance of fine aggregates (sand and garnet) used in the concrete production [8]

2. Spent Garnet

2.1 Composition of Spent Garnet

Spent garnet is normally treated as a waste product when the garnet is degraded and no longer can be reused in certain activities. Garnet has advantageous properties in its angular fractures, hardness and ability to be recycled. This make garnet to be an ideal and beneficial material for numerous abrasive applications. Garnet represents a large group of rock-forming minerals where it has the general chemical composition formula of $X^3Y^2(SiO^4)$.

Garnet is widely used as industrial materials in many fields such as waterjet cutting, abrasive blasting, water filtration, abrasive powder and others. Garnet can be recycled up to 5 times until degrade to a certain extend and be discharged which known as spent garnet [8].

The mineral garnet is commonly found in metamorphic and to a lesser extent, igneous rocks. Garnet commonly can be found in metamorphic rocks which are formed through subjected to high temperature and pressure forces within the Earth, such as mica schist, marble and skarns. While granite is the igneous rock where garnet forms and exists. Garnet can be extracted by open pit mining method on the ground. It is then will be removed from the surrounding rock, and followed by the process of washing, screening and quality sorting for using purposes.

Spent garnet is the universal appellation for a cluster of composite silicate natural resources with comparable crystal-like assemblies and varied chemical configurations [6]. By referring to the data obtained, the chemical compositions for garnet are SiO^2 (33.7%), Al^2O^3 (13.9%), Fe^2O^3 (43.1%), TiO^2 (0.78%), CaO (4.15%) and MgO (2.91%) [13].

Garnet is metallic-free iron, making it ideal for all surface preparation fields, including stainless steel, anti-magnetic steel, and all other alloys. It has many advantages such as recyclable, low health risk, low dusting, fast cutting, low-free content of silica, and with no measurable heavy-metal concentrations. Garnet is well-matched to most fields of the surface preparation industry with and without following coatings, in particular shipyards, new construction, conversion, and restoration, including anti-magnetic and other special steels, as well as aluminium superstructures and aluminium and fibreglass hulls.

2.2 Spent Garnet and Environmental Pollution

In this era, countries are more emphasis on the rapid growth of industries especially in construction industries. Large scale development in the built environment and its physical infrastructure is needed, these are seemed to be the vital elements as in a developed country. However, this practice has largely exploited huge number of natural resources until a certain extend that causes environmental issues. There is concern about how to improve construction practices to minimize their detrimental effects on the natural environment. In addition, the practice of sustainable intercession is an urge to be taken during the process of creating built environment, rather than try and change things after the fact. The principle of sustainability states that it does not mean the eradication of adverse impact, which is an impossible vision at present, but rather the reduction of it to a certain reasonable level. Sustainable development plays as a vital role in construction industry.

Sustainable development is the important key to maintain the balance of human needs and environment while offering a better living and lifestyle and preserving natural resources and ecosystems without disturbing the future generation's needs. Nowadays, there are many ways to implement this practice with the concepts in reducing environmental impact.

This can be practice by constructing a green building through enhancing in the factors of energy efficiency and waste management. In the part of constructing green building, the environmental issues from sand mining can be improved by using other replacements. This is significant to construct a green concrete. Green concrete known as a concrete that uses waste material alternative to one or more of its raw materials. It also defined as where the process of its production does not harm the environment and lead to destruction of ecosystem and meanwhile, it offers high performance and beneficial in life cycle sustainability. There are many successful results of the sand replacement for concrete in previous research such as waste products include discarded tires, plastic, glass, burnt foundry sand, Coal Combustion By-Products (CCBs) and so on. These waste products can offer positive effects on the concrete performance with optimum percentage usage. Moreover, the use of waste products in concrete also beneficial in making cost of concrete more economical and largely helps in reducing environmental pressure of over exploiting natural resources and disposal.

The total utilization of industrial garnet in worldwide was estimated as 440k tons in 2002 [14]. It is widely used as industrial materials in many fields such as waterjet cutting, abrasive blasting, water filtration, abrasive powder, and others [8]. In the part of garnet extraction, the mining process poses a threat to air pollution. This is because mining sector is one of the major emitters of greenhouse gases due to the consumption of diesel fuel [15]. By the method of open-pit mining, the soil is removed from an area to extract the rock resources. This method can easily damage agricultural areas [9].

In Malaysia, it is revealed that the Malaysian Marine Heavy Industry (MMHE) imported approximately two thousand tons of garnet in 2013 for sandblasting ship purposes. The technique of abrasive blasting is required prior to coating and paint for the ship surface. However, this creates a large amount of exhausted garnet wastes mixed with paint chips and oil. Garnet can be reused up to 5 times. When it degrades to an extent, it will be discharged from the shipyard. Discharging spent garnet in river and ocean from shipyard will directly pollute the quality of water resources and the aquatic life as well. Some industries may discharge such waste in landfills, and it potentially brings contamination when it enters in the waterways during the flood or through runoffs. Thus, the unproper way of discharge spent garnets became a hazard to environmental issues and humans [8].

On the other hand, due to its benefits properties in durable, hardness, and ability to be recycled, the use of spent garnet should be explored in other further applications. This could be a great green alternative material associated with environmental problems.

According to the one of the articles by The Fabricator pointed out that "disposing of used garnet isn't free, and costs add up over time". Hence, disposal cost and landfill needed to store the waste can reduced by replacing of aggregates in concrete with waste gamet. Apart from that, Environmental Quality (Scheduled Wastes) Regulations, 2005 in Malaysia requires the proper packaging, marking and handling for hazardous materials. Therefore, flexible intermediate bulk containers (FIBCs) are recommended in the guideline for packaging, labelling and storage of scheduled wastes in Malaysia to store contaminated garnet. Hence, a good practice can implement for all parties by following the appropriate ways to manage the waste in Malaysia.

3. Properties of Spent Garnet as Construction Material

3.1 Physical Properties of Spent Garnet

Garnet comes with variety of colour according to its chemical components but commonly with reddish shades. The spent garnet obtained from southern Johor in Malaysia appeared to be in pink to red colour. The smell of spent garnet is odourless.

According to Table 1, the spent garnet displayed a greater value of specific gravity than sand, which is 3.0 [8]. This phenomenon is due to the high content of iron oxide (Fe^2O^3). The value of water absorption is 6% greater than the overall limit suggested for fine aggregates by BS EN 1097-6 [16], which is 3%. The amount of bulk density is higher than required in regular concrete due to reduced void content, and it could have occupied pore and the pore structures optimized. It does lead, however, to high water consumption.

With the present of oxygen and moisture, the ferrous hydroxide in spent garnet is converted to gamma iron oxide (γ-Fe^2O^3) and a thin passive film is formed on the surface of the steel which can avoid corrosion of reinforced concrete structure by environment of future use.

Table 1 - Physical properties of spent garnet [8]

Properties	Spent garnet	River sand	Permissible limit	Relevant standard or reference
Specific gravity	3.0	2.6	2.6 – 2.7	[17]
Finesse modulus	2.05	2.66	2.3 – 3.2	[18]
Hardness	7.5	6	1 – 10	Mohs scale of mineral hardness
Bulk density	1922 kg/m^3	1640 kg/m^3	1300 - 1750	[19]
Water absorption	6%	3%	2% - 3%	[16]

3.2 Grading of Spent Garnet

The coefficient of grading for spent garnet is higher than one makes it expressed as well-graded, which was 1.02 as presented in Fig. 3. The particle size distribution of material occurs inside the upper and lower limits of fine aggregate medium grading limits stated by BS 882 [20], which is equivalent to the BS 812-103.1 [21] classification of zone II. The percentage retained for 5 mm sieved was 0 per cent, which was within the prescribed grading criteria for fine aggregates within the 0-5 per cent range of BS 882 [20]. This statement stated that the classification of the spent garnet for fine aggregates is suitable for concrete production.

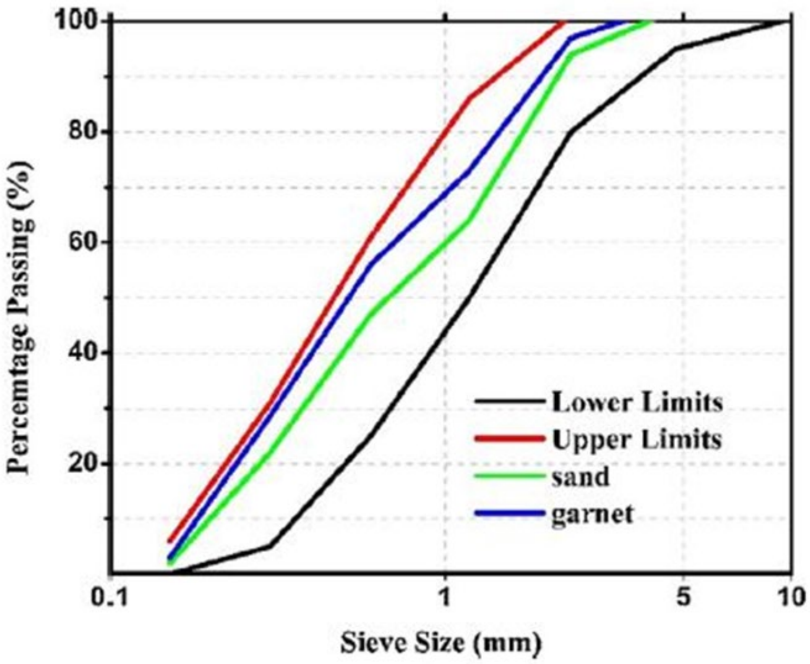

Fig. 3 - Percentage passing of spent garnet [8]

3.3 Chemical Properties of Spent Garnet

Based on Table 2, the primary component for the chemical composition of spent garnet was iron oxide (Fe^2O^3) which was 43.06%. The silicon oxide (SiO^2) is 33.76%, and alumina (Al^2O^3) content is 13.88%. Due to the high composition of iron oxide, it is responsible for the reddish colour of spent garnet. Nevertheless, in the chemical composition, the presence of copper, zinc and lead can disturb the hydration development, and there has been no trace of sulphur trioxide in it.

The chemical composition will possibly affect the hydration process, mechanical properties of concrete mixture, etc. However, the potential of spent garnet as sand replacement can be further investigated through experimental testing.

Table 2 - Chemical properties of spent garnet [8]

Chemical Compounds	Weight % of spent garnet	Weight % of sand
Fe^2O^3	43.06	0.7
SiO^2	33.76	96.4
Al^2O^3	13.88	-
CaO	4.15	0.14
MgO	2.91	-
MnO	1.08	-
TiO^3	0.78	1.1
K^2O	0.14	-
P^2O^5	0.21	-
ZnO	0.06	-
Cr^2O^3	0.05	-
(LOI)	-	1.1

4. Spent Garnet in Concrete Properties

4.1 Spent Garnet in Concrete

There were a lot of researches completed by adjusting different sorts of recycled waste materials in substituting the material of concrete. Those researchers have proven that modified concrete could enhance the properties of concrete and reduce the landfills along with the environmental issues.

Spent garnet is one of the studied materials that can replace fine aggregates in concrete mix. Since the industrial waterjet cutting is mined for removal and thus the cast-off garnet sand is collected to be used sporadically as fine aggregates in construction and road infrastructure. According to Lawrence Livermore National Laboratory, the waste from waterjet cutting was studied to evaluate the likelihood of garnet sand in transforming as a concrete aggregate and trench backfill [22]. Besides, in order to minimize the cost of waterjet cutting, a process for restoring the abrasiveness of garnet sand was conducted at Tomsk Polytechnic University. Garnet waste substitutes quartz sand in both cases. The findings supported the likelihood that cast-off garnet sand could be used as aggregates in concrete. However, there is no confirmation yet for its application as trench backfill [22].

The blasting of garnet is widely applied for purposes such as the preparation of pre-finished surfaces, in other words. the preparation of surfaces prior to painting or other coatings used in ship structure building, reconstruction, repair, and maintenance [13]. Fundamentally, the recyclable ability of garnets composed with their angular fractures and hardness properties will be beneficial for abundant abrasive functions. Significant manufacturing applications such as abrasive blasting media, antiskid surface abrasive powders, granules of water percolation, water jet cutting, etc. Abrasive blasting methods are applied for the preparation of surfaces for painting and coating. This method is selected and applied for vessel building, ship repair and maintenance operations.

4.2 Compressive Strength

Research by Muttashar, et al [6] has investigated on the effect of spending garnet as sand replacement in self-compacting geopolymer concrete (SCGPC) as presented in Fig. 4. The outcome showed the workability of SCGPC increased with the increasing amount of spent garnet used. The flexural, splitting tensile strengths were considered lower than control specimens. However, the optimum percentage of spent garnet was 25% for achieving enhanced SCGPCs.

Study by Khiyon, et al [23] has revealed that the effects of spent garnet in high-strength concrete are subjected to elevated temperature. Based on the study by Khiyon, et al [23], the compressive strengths at 28 days for 20% replacement and 40% replacement is 62.26 and 63.61 MPa; furthermore, those of 60%, 80%, and 100% replacement decreased with the value of 59.17, 58.33 and 57.89 MPa, respectively. From the fire test, 40% of spent garnet gave slightly better protection for steel bars. For the pull-out test, the results showed that 40% of spent garnet has higher bond strength. It concluded that 40% of spent garnet as sand replacement in high strength concrete showed excellent performance in terms of the strength of concrete subjected to fire.

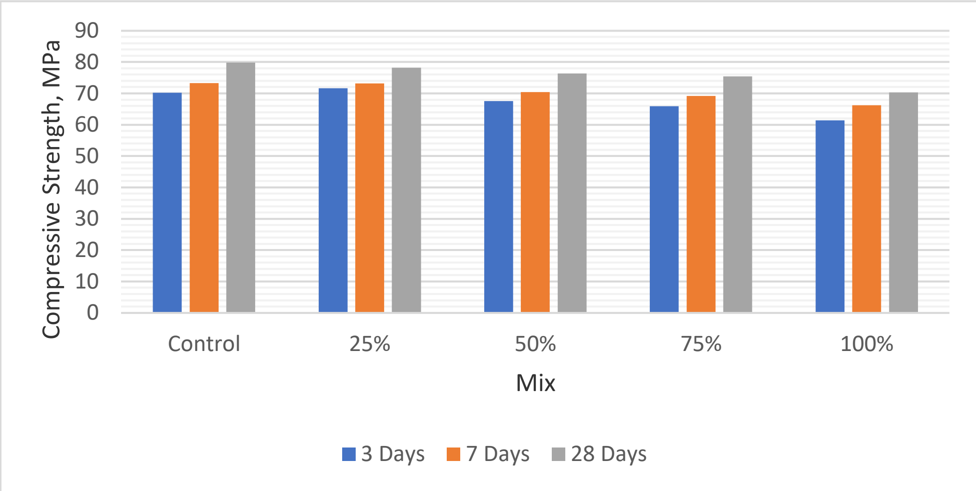

Fig. 4 - Compressive strength result obtained by [6]

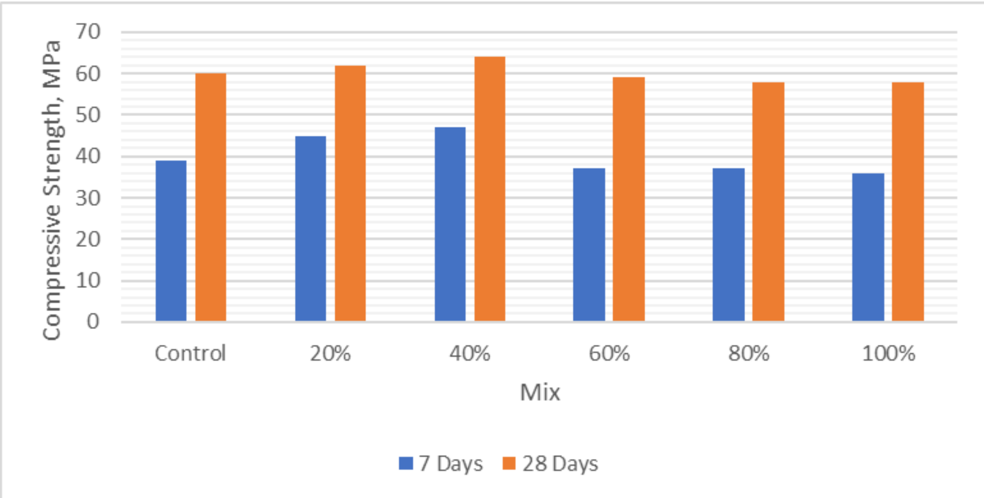

Fig. 5 - Compressive strength result obtained by [23]

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5. Conclusion

The findings of 23 studies published in the last ten years were presented in this review paper. The following conclusions have been reached as a result of this extensive review of research data. Firstly, the ability of spent garnet to be used as an alternative material to sand. The spent garnet material was found to be well graded as its grading fell to zone II within the specified limits of BS 812-103.1 [21]. The chemical composition of spent garnet revealed iron content, alumina, and high silica. The spent garnet showed the value of specific gravity of 3.0, which is higher than that of natural sand (usually varies from 2.6 and 2.7) [17]. The high specific gravity of spent garnet was ascribed to the elevated contents of iron oxide (Fe^2O^3) in it. The water absorption value of 6% was higher than the maximum limit of 3% recommended by BS EN 1097-6 [16] for fine aggregate. The result showed from [8] study demonstrated that it is possible to apply spent garnet in concrete. Next is the performance of spent garnet in concrete. Based on a study by [6], the spent garnet reached optimum percentage at 25% replacement regarding both mechanical properties and flowability. Beyond this, it will cause a reduction in the strength of SCGPCs. While in the study by [23], the strength of a concrete increases in 20 and 40% replacement of spent garnet. Beyond this, the strength decreases in value. Thus, it can be said that the optimum percentage of spent garnet in concrete falls within 20% to 40% replacement of partial fine aggregates. Beyond this, it will reduce the workability of spent garnet in concrete.

Spent garnet is a promising waste material to be used development of construction material especially concrete. The properties of this waste material with higher hardness and finer size makes it feasible to be utilized as partial fine aggregate in concrete or brick production. Findings that discovered the combination of right quantity of spent garnet successfully increases the concrete strength. Creative mix proportioning approach that would enable higher quantity of spent garnet to be used in various special types of concrete manufacturing such as lightweight aggregate concrete, fiber reinforced concrete, polymer concrete, architectural concrete and many other types should be explored as well. More discovery on spent garnet use in construction building material research need to be carried out to expand its application in construction industry.

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