Dijlah Journal of Engineering Science (DJES) Vol. 3, No. 2, June, 2026, pp. 391-400
ISSN: Printed: **3078-9656, Online: 3078-9664**, paper ID:173

Effect of High Temperatures on the Mechanical Performance of Geopolymer Concrete Incorporating Treated and Untreated Recycled Concrete Aggregates

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Article Info

Article history:

Received Marh., 16, 2026
Revised Apr.,20.2026
Accepted Jun.,15,2026

Keywords:

Concrete,
GGBS,
Fly Ash (FA),
Recycled coarse aggregate,
Treated recycled aggregates,
untreated recycle coarse aggregate,
sodium metasilicate

ABSTRACT

Geopolymer concrete is a sustainable substitute for Portland cement, which can resolve the environmental issues caused by Portland cement. The study aimed to investigate the use of natural aggregates (NA) or recycled coarse aggregates (RCA) in geopolymer system which is seen as greener material. In their study, the authors utilize Fly Ash (FA) and Ground Granulated Blast Furnace Slag (GGBS), which are industrial waste materials, activated by sodium hydroxide and sodium silicate solution. The research contrasted three different mixes. The mixes that are evaluated are reference R-GNA made with natural aggregate, GTRA geopolymer with treated recycled aggregates, and GUTRA geopolymer with untreated recycled aggregates. One of the focuses of this work is the improvement of RCA quality through a coating process with sodium metasilicate to seal surface pores and micro-fissures. To investigate the thermal stability of these mixtures, they were subjected to a temperature of 700°C for two hours. The Scanning Electron Microscopy (SEM) was used to characterize the microstructural changes and efficiency of the aggregate treatment. The experiment results show that the untreated RCA has high porosity which leads to increased moisture leakage and thereby decreased durability in comparison to natural aggregates. The use of sodium metasilicate enhanced the mechanical performance of recycled aggregate mixtures significantly. Examination of fire injured concrete showed that the treated RCA concrete with TRCA presented with less micro-cracking and gel degradation than untreated RCA concrete which exhibited severe matrix damage. The use of treated recycled aggregates in geopolymer concrete can optimize the compressive strength as well as residual properties after exposure to heat. Thus, it supports sustainable building solutions.

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1. INTRODUCTION

Due to outstanding versatility and long-term structural performance, concrete has emerged as the world’s primary building material. The ecological footprint of its major binder, Portland cement, is troubling. The cement industry is presently answerable for roughly 7 percent of all the carbon dioxide emitted globally [1], besides its huge consumption of energy and raw natural materials. In addition to the ecological concerns, conventional cement-based concrete is subject to various mechanical drawbacks, which include a low tensile capacity leading to cracking and further degradation of the structure [2,3]. To address these shortcomings, it is necessary to introduce steel reinforcement, though this considerably increases the cost and complexity of construction [4]. Furthermore, it's easily damaged in aggressive chemical environments, such as acidic or salty environments, which leads to early failure and expensive repair costs [5].

Because of these disadvantages, there is a need for more sustainable and durable options. Geopolymers are a new class of binders which can serve as a substitute for cementitious materials [6]. Binders are made via chemical activation of precursors rich in aluminosilicates such as fly ash, slag or calcined clays by concentrated alkaline solutions (usually sodium or potassium hydroxides and silicates) [7]. Through the geopolymerization process, the formation of a three-dimensional poly-condensed framework made of aluminosilicate chains takes place, which gives a binding strength to the material [10].

Geopolymer concrete (GPC) has various benefits, notably drastically reducing greenhouse gas emissions while reusing industrial by-products [8]. The ability of GPC to develop strength quickly may shorten the construction schedule of such structures compared to normal concrete [7]. GPC offers various advantages, but it also suffers from some industrial problems such as a fairly high alkaline activators price and not universal standards [9, 11, 12]. From practical perspectives, a high viscosity of the geopolymer binders may also reduce workability causing difficulty in casting and segregation of the mixture [13, 14].

Nonetheless, the microstructural characteristics of GPC are usually more superior to ordinary concrete. The process of geopolymerization produces a finer and more compact pore structure, making the material more resistant to water and freeze-thaw cycles [6]. Geopolymer binders possess excellent thermal stability, which means that they maintain their structure well and retain a higher proportion of original strength than Portland Cement-based systems at elevated temperatures [15]. Nonetheless, further research is still required to address the issues of long-term fire resistance and the local availability of good quality raw materials for other infrastructure [16].

2. MATERIALS AND METHODS

2.1. Materials

2.1.1. Binder

The binder of geopolymer concrete was produced using fly-ash (FA) obtained from Ennore Thermal Power Plant. The other aluminosilicate precursor used in producing the binder is ground granulated blast furnace slag (GGBS). The chemical oxide compositions of both precursors are presented in Table 1. Physical characterization revealed that the specific gravities of FA and GGBS were 2.2 and 2.9, respectively. In addition, the specific surface areas were measured at $410\ \mathrm{m}^2/\mathrm{kg}$for fly ash and $418\ \mathrm{m}^2/\mathrm{kg}$for GGBS, reflecting their fine particle nature and their suitability for effective geopolymerization.

Table 1. Oxide composition of FA and GGBS.

Oxides	**FA (%)**	**GGBS (%)**
SiO_2	47.67	43.5
Al_2O_3	27.73	12.1
Fe_2O_3	18.42	1.0
Cao	5.11	40.7
MgO	2.65	1.2
C_3A	0.34	--
K_2O	--	0.7
CI	--	0.02
LOI	3.71	0.2

2.1.2. Aggregate

In this study, natural gravel together with recycled concrete aggregate (RCA) was used as the coarse aggregate fraction in concrete production. Natural sand was employed as the fine aggregate, with a maximum particle size of 4.75 mm, whereas the coarse aggregate was graded to a maximum size of 10 mm in accordance with the requirements of IQS No. 45/1984 [17].

The physical characterization of the aggregates indicated that the specific gravity of the coarse aggregate was 2.6, while that of the fine aggregate was 2.7. In addition, the bulk densities of the coarse and fine aggregates were determined to be 1540 kg/m³ and 1821 kg/m³, respectively.

To enhance sustainability and minimize construction costs, crushed concrete obtained from demolished structures, specifically pre-tested laboratory specimens, was reused as recycled coarse aggregate with a nominal maximum size of 12.5 mm. Because of the relatively high porosity of RCA, sodium metasilicate pentahydrate was used as a surface treatment, based on Spaeth and Tegguer (2013) method. The objective of this treatment was to close the internal pore network to improve resistance to fragmentation and lower water absorption without any hydrophobic effect. The grading of all the aggregates was carried out as per IQS No. 45/1984 [17].

2.1.3. Alkaline Activator

The alkaline activation system was made of sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3) having a silicate modulus of 2.5. NaOH complies with ASTM E291-09 [18]. The specific gravities of activators like sodium hydroxide solution showed 1.29 and sodium silicate solution showed 1.551. The preparations of alkaline activators were selected and mixed proportionately for effective geopolymerization. The mixture proportions are given in Table 2.

Table 2. Composition of Geopolymer Mixtures

Mix Type	Fly Ash(kg/m3)	GGBS (kg/m3)	Fine Agg. (kg/m3)	Nat. C.A. (kg/m3)	TRCA(kg/m3)	UTRCA(kg/m3)	Alkalin(kg/m3)	Water(kg/m3)	S.P %
R-GNA	100	300	720	1100	0	0	180	40	3
GTRA-100	100	300	720	0	1100	0	180	40	3
GUTRA-100	100	300	720	0	0	1100	180	40	3

2.2. Methods

2.2.1. Casting & Curing

The fabrication process started with the dry mixing of the binder materials and fillers to facilitate the uniform distribution of the constituent particles and the subsequent gradual addition of the alkaline activator solution. Mixing continued until a uniform and workable matrix was obtained. The new properties of the geopolymer mix were assessed prior to casting. The prepared mixes were poured into standard molds for further mechanical testing.

The specimens were kept in the molds for 24 hours to get initial setting and demolded thereafter. The experimental program indicated that geopolymer specimens were cured at room temperature and in the oven. Following the demoulding, the specimen were kept at a temperature of 27 to 30°C. After production, the geopolymer specimens were subjected to outdoor ambient conditions for 28 days for long-term curing. In contrast, the reference conventional concrete mixtures containing both natural and recycled aggregates were conventionally cured by water in laboratory tanks for 28 days.

2.2.2. Testing

The mechanical properties of the developed geopolymer concrete were evaluated through a series of standard tests. The compressive strength was done in accordance to BS 1881: Part 116: 1989 [19]. Three cube specimens of 150×150×150mm were cast for the 28 days curing and tested in a hydraulic compression machine of 2000 kN capacity.

According to ASTM C496 [20], the indirect tensile strength (splitting tensile strength) was determined on four cylindrical specimens, 150×300mm, of each concrete mix. In addition, flexural strength was evaluated in accordance with ASTM C78-2005 [21] using three prism specimens of $150 \times 150 \times 500$mm for each mixture.

The static modulus of elasticity was assessed based on ASTM C469 [22]. This test was performed by analyzing the stress–strain response of hardened concrete under different curing conditions, using three cylindrical specimens of 150×300mm for each experimental mixture to ensure reliable results.

2.2.3. Heating Program

The purpose of the experiment was to evaluate the residual strength of the GPC that had been developed. To achieve this, the samples were placed in the oven, the oven door was closed, and the oven was ignited using an external device. The temperature rose rapidly, reaching the target temperature within a few minutes. During the daytime warm-up test, the oven temperature reached the target temperature 700 C for two hour according to Eurcode (EN 1991-1-2). A comparison was made between two geopolymer concrete mixes (GTRA-100,GUTRA-100) to determine the effect of heat and the effect of the aggregate used in the first mix. The first mix used treated recycled aggregate at a 100% replacement rate, and the second mix used untreated recycled aggregate at a 100% mixing rate.

Plate (1) Burning the Samples

2.2.4. Scanning Electron Microscope

The Scanning Electron Microscope (SEM) uses a focused beam of electrons to scan samples to get data on surface morphology and composition by the interaction. The resolution of the SEM was not less than 8 nm with an increased depth field and an accelerating voltage of 20 kV. The samples are procured from 28-d aged CS tested specimens to examine the polymerization rate and sufficiency of geopolymer gel in the matrix.

3. RESULTS AND DISCUSSION

3.1. The compressive strength (f_c')

The compressive strength (f_c') is one of the most important parameters used to assess the quality of hardened concrete. It is also the most specified characteristic of concrete. The results of the experiments indicated that compressive strength of GUTRA-100 mixture considerably decreased compared to reference R-GNA mix, when natural aggregates (NA) are replaced with untreated recycled coarse aggregates (UNTRCA).

On the contrary, the specimens manufactured with treated recycled aggregates (GTRA - 100) showed a noticeable improvement in compressive strength compared to the untreated recycled aggregate mixture (GUTRA - 100). While the treatment process clearly improved the mechanical performance, the resulting strength values were still somewhat lower than those for geopolymer concrete with natural aggregates. According to these results, the compressive behavior of geopolymer concrete seems to be strongly reliant on either the surface properties or overall quality of the aggregates which affect the density and microstructure of the geopolymer matrix.

Table (2) All beam mixes were found to have 28 days compressive strength results.

Mix Name	NA %	TRCA %	UNTRCA %	f'_c (MPa)	% Decrease in f'c (due to increase in RCA)	% Increase in f'c (due to replacement in UNTRCA to TRCA)
0-(R-GNA)	100	--	--	46.285	Reference	--
2-(GTRA-100)	--	100	--	42.93	-7.25	17.4
3-(GUTRA-100)	--	--	100	36.57	--	Reference

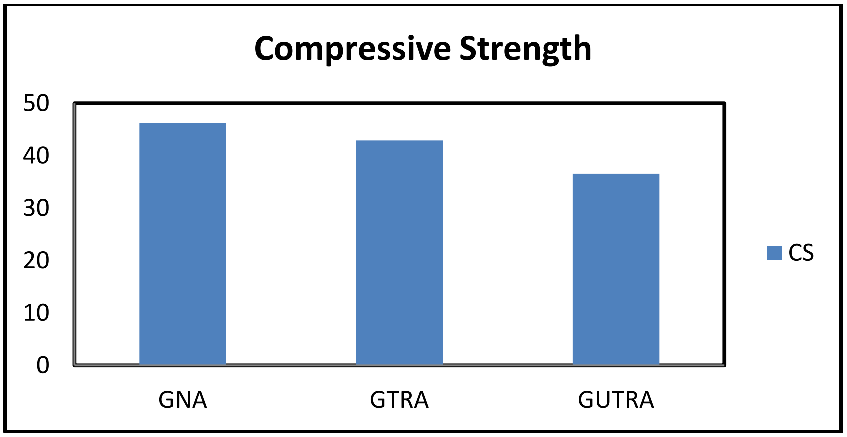

Figure (1) Compressive strength results

3.2 Splitting Tensile Strength (f_t)

The tensile strength is a vital parameter in the assessment of structural performance of concrete since most cracking and failure mechanisms are primarily associated with tensile stresses and also to environmental factors like temperature and shrinkage. Theoretically possible, direct tensile testing practically is only possible due to issues of alignment of the specimen and stress concentration at the gripping ends. Consequently, the splitting tensile test was selected as the most appropriate and practical test using standard 150×300mm cylindrical specimens.

The findings of the experiment were presented. Initially, the tensile strength values measured or obtained for all the geopolymer concrete mixtures were less than the theoretical equation. The tensile performance of the cement paste mixtures are also strongly influenced by the type of aggregate. It was observed that natural aggregate (NA) mixtures had higher tensile performance than the recycled aggregate mixtures. There exists a positive correlation between the ratio of natural aggregate and the tensile strength of the geopolymer concrete.

Besides, TRCA resulted in improved tensile performance as compared to UNTRCA. The sodium metasilicate treatment led to a decrease in water absorption of recycled aggregate as well as a better quality of the interfacial transition zone (ITZ). Consequently, the treated aggregate surface exhibited a stronger bond with the geopolymer paste, which enhanced the tensile loading resistance of the geopolymer concrete.

Table (3) Experimental and Theoretical Splitting Tensile Strengths

	NA	TRCA	UNRCA	ft (Experimental)	ft (Theoretical)	% Decrease	% Increase in

Mix Name	**%**	**%**	**%**	**(MPa)**	**(ACI 318M 2011) (MPa)**	**in f't (due to increase in RCA**	**f't (due to replacement in UNTRCA to TRCA)**
0-(R-GNA)	100	--	--	3	3.8	Reference	--
2-GTRA-100)	--	100	--	2.32	3.669	-22.67	9.62
3-(GUTRA-100)	--	--	100	2.14	3.386		Reference

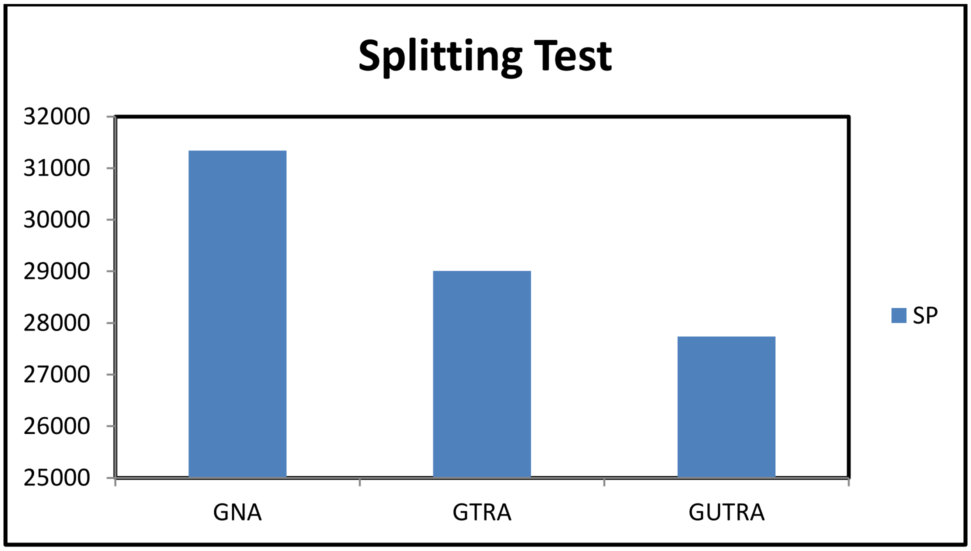

Figure (2) Splitting Tensile Test results

3.3 Flexural Strength (fr)

The modulus of rupture (fr) is the maximum bending stress that a concrete specimen can withstand before failure. It was found out in this study by testing plain concrete prisms of 150×150×500mm under standard two-point loading system with simple supports.

The results of the experiments showed a positive relationship of compressive and flexural behaviour for all the geopolymer concrete mixtures as per compressive strength. The flexural strength predicted in theory was higher than what was measured experimentally.

The mixtures made with natural aggregates (NA) had better flexural performance as compared to mixtures made with recycled concrete aggregates (RCA). The contribution of RCA-based mixtures to lower strength was mainly due to the water absorption capacity of particles and the presence of old mortar on the surfaces of recycled aggregates. The characteristics that contribute to poor processing and the development of weak zones within a geopolymer produce a low aggregate.

Nonetheless, the mechanical behavior exhibited greater improvement more pronounced than other treatments and control sample. By forming a layer of sodium metasilicate over the tile surface it helps in sealing the pores and limiting water absorption. This treatment enhanced the mechanical quality of the treated recycled coarse aggregate (TRCA) and improved the interfacial transition zone (ITZ), thereby increasing the flexural strength of the hardened geopolymer concrete.

Table (4) Experimental Flexural Strength and Theoretical Flexural Strength

Mix Name	**NA %**	**TRCA %**	**UNTRCA %**	**fr (experimental)**	**Fr (theoretical)**	**% Decrease in f'r (due to increase**	**% Increase in f't (due to replacement in**

						in RCA)	**UNTRCA to TRCA)**
0-(R-GNA)	100	--	--	3.985	4.128	Reference	--
2-(GTRA-100)	--	100	--	3.14	4.138	-2.12	4.946
3-(GUTRA-100)	--	--	100	2.99	3.749	--	Reference

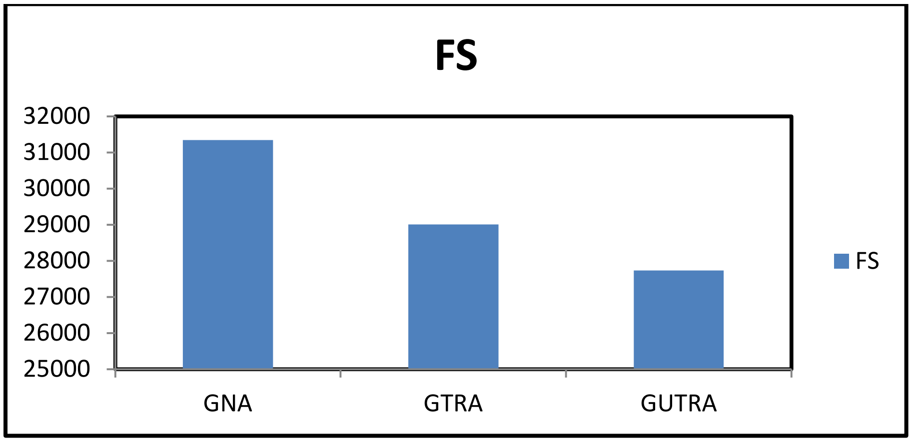

Figure (3) Flexural Strength Test results

3.4 Static Modulus of Elasticity (Ec)

Elastic modulus is the ratio of stress to strain in the linear portion of an extension curve. The measurement of strain changes with stress has now been carried out under compression of concrete cylinders, after dial gauges were attached to them. It has been shown that the modulus of elasticity increases as compressive strength increases.

Table (4-6) Experimental & Theoretical Modulus of Elasticity Values

Mix name	**NA %**	**TRCA %**	**UNTRCA %**	**E_c (experimenta) (MPA)**	**E_c (theoretical) (MPA)**	**% Decrease in E_c (due to increase in RCA)**	**% Increase in E_c (due to replacement in UNTRCA to TRCA)**
0-(R-GNA)	100	--	--	31342	31975	Reference	--
2-(GTRA-100)	--	100	--	29010	30794	-7.44	4.6
3-(GUTRA-100)	--	--	100	27735	28422	--	Reference

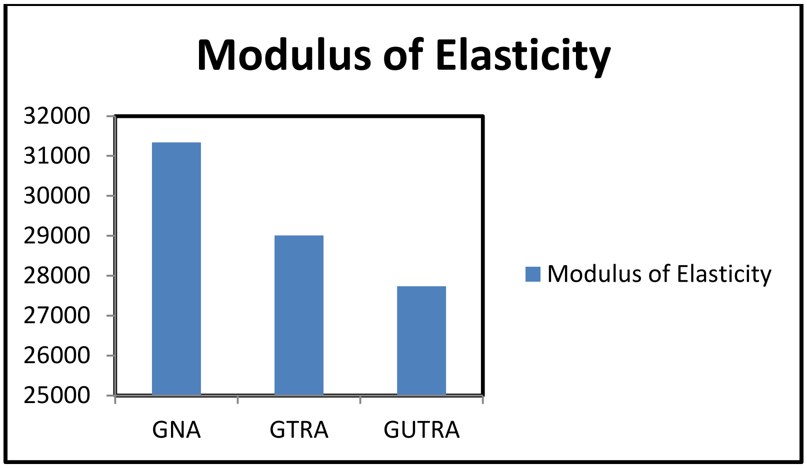

Figure (4) Static Modulus of Elasticity Test results

3.5 Scanning Electron Microscope Tests

Scanning electron micrographs of the chosen concrete mixes made with 100% recycled concrete aggregate before firing (no treatment of the aggregates) are shown in Figure 1.

As seen in Figure 1, the GUTRA-100 mix comprised 75 % slag and 25 % fly ash and recycled concrete aggregate 100% with thick paste and dense gel forming polymer geopolymer. Because the particle size of slag is finer than that of fly ash, it can help reduce pore size. Observation using optical and SEM indicates good bonding at the interfacial zone. The recycled concrete aggregates had a rough topography and porous structure, which helped them bond tightly with the matrix and improve the compactness and strength of the composite.Figure 2, an SEM image of 100% recycled concrete aggregate for GUTRA-100 mix after exposure to 700 °C for 2 hours, shows that small microcracks are present in the matrix due to the production process. Employing a high slag content results in significant activation and, subsequently, high-geo-polymeric products, as evidenced by the absence of unreacted slag and GP microspheres under the microscope. Due to the production of microspores in the matrix because of water evaporation, compressive strength is diminished. When the geo-polymer is heated to 700 °C, dazzling crystals form in the tiny crevices and holes. Microcrack size and crystal content both increased in a geo-polymer paste heated to 700°C, degrading the microstructure and speating the aggregate.

Figure 3 presents scanning electron micrographs of the selected concrete mixes prepared with GPC: 100% recycled concrete aggregate treated with sodime silicate before exposure at high temperatures used to improve its poor properties (high absorption, roughness It helps reduce water absorption and increase density because it treats the aggregate surface and seals pores, through chemical treatment. It shows an SEM that sodium silicate acts as an activator and bonding agent, increasing the concrete's compressive and tensile strengths and reducing porosity. It exhibits a thick paste and thick geopolymer gels. It can be used at high replacement ratios to produce environmentally friendly, high-strength GPC. Figure 4 shows an SEM image of the treated recycled concrete aggregate for GTRA-100 mix after exposure to 700 °C for 2 hours. A phase transformation in the quartz crystal leads to thermal expansion and internal cracking. Additionally, with increasing temperature, the strength loss is particularly pronounced between 400 and 600 °C. The expansion of crack width and the poor interfacial zone between the recycled and treated aggregates result in wider cracks and voids, as illustrated by SEM images.

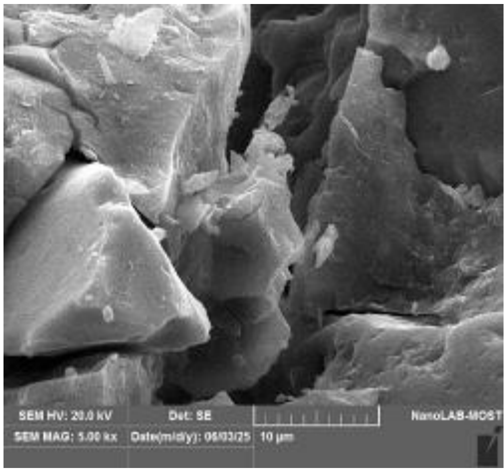

Plate (1) SEM test result of GUTRA-100

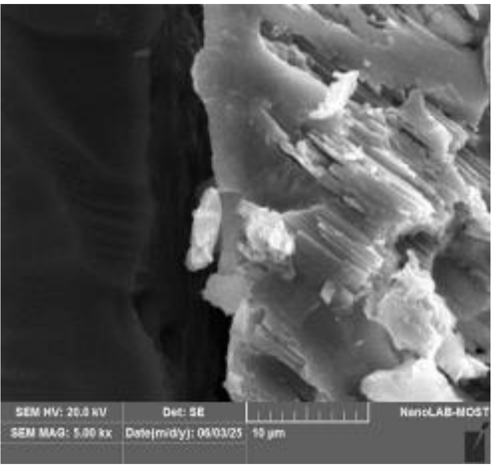

Plate (2) SEM test result of GUTRA-100 –Fire

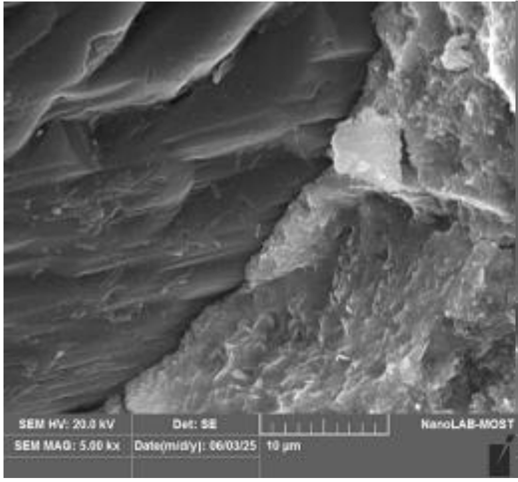

Plate (3) SEM test result of GTRA-100

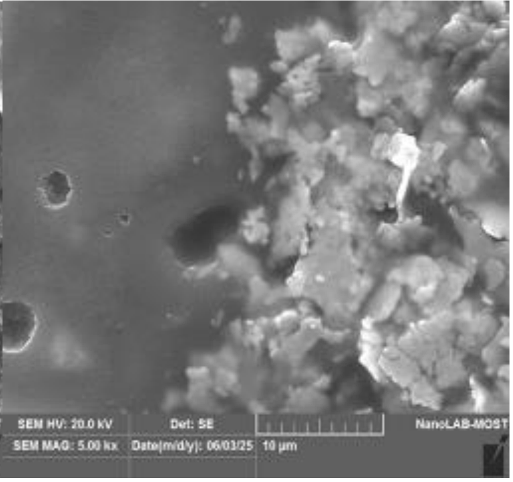

Plate (4) SEM test result of GTRA-100-F

4. Conclusions

Based on the experimental evaluation of the mechanical properties of geopolymer concrete incorporating natural and recycled aggregates, several important conclusions can be drawn.

A clear reduction in compressive strength was observed when untreated recycled coarse aggregate (UNTRCA) was used, as the strength decreased from 44.28 MPa in the natural aggregate mixture to 36.57 MPa. Nevertheless, treating the recycled coarse aggregate with sodium metasilicate significantly improved the compressive performance, increasing the strength to 42.93 MPa at 100% replacement, which was very close to that of the reference mixture.

When considering splitting tensile strength, the effect of UNTRCA on tensile and flexural performance was low as it caused a drop of 28.67% compared to natural aggregate mixtures. The therapy applied aided to regain some of the loss which was reduced at merely 22.66%. The flexural strength data showed a similar trend; the modulus of rupture of UNTRCA specimens was 24.96% lower than the natural aggregate reference. On the contrary, the specimens made with treated recycled aggregate (TRCA), exhibited significant improvement, with a mere 2.63% reduction.

The fracture response and microstructural observation confirmed that the cylinders with natural aggregate are able to carry the load after cracking better than untreated recycled aggregate. The use of RCA improved the interfacial transition zone (ITZ) and limited the initiation and propagation of microcracks in the matrix of geopolymer.

Also, aggregate type affected the static modulus of elasticity. The E_c value of the reference natural aggregate geopolymer concrete is 3.134 GPa which decreased to 2.773 GPa when untreated recycled aggregates were used. After being treated, the modulus reached 2.901 GPa indicating an internal structure that is denser, stiffer and more coherent.

ACKNOWLEDGEMENTS

Authors thank University of Dijla for this opportunity.

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