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Research Article

Strength and abrasion performance of recycled aggregate based geopolymer concrete

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ABSTRACT

This experimental work evaluated geopolymer concrete containing fly ash and slag by partial replacement of natural coarse aggregate (NCA) with recycled coarse aggregate (RCA) to manufacture environmental-friendly concrete. The proportion of recycled aggregates considered consists of 10%, 20%, 30%, and 40% of the total coarse aggregate amount. Also, a steel fiber ratio of 0.3% was utilized. The mechanical properties and abrasion resistance of fly ash/slag-based geopolymer concrete were then assessed. Majorly, the mechanical strength of the concrete samples decreased by the increase of RCA content. The geopolymer concrete with 40% RCA gave 28.3% lesser compressive strength and 24% lower splitting tensile strength than NCA concrete at one year. Also, the flexural strength of concrete specimens was reduced by 35% (from 5.34MPa to 3.5MPa) with the incorporation of 40% RCA. The incorporation of 30% RCA caused 23% and 22.6% reduction in compressive strength at 56 days and one year, respectively. The flexural and splitting tensile strength of the specimens was not significantly reduced (less than 10%) with the inclusion of a recycled coarse aggregate ratio of up to 30%. Furthermore, the abrasion wear thickness of every concrete sample was less than 1 mm. RCA inclusion of 20% produced either insignificant reduction or better strength results compared to reference mixtures. As a result, it was considered that the combination of 0.3% steel fiber and 20% recycled coarse aggregate in fly ash/slag-based geopolymer concrete leads to an eco-friendly concrete mix with acceptable short and long-term engineering properties that would lead to sustainability in concrete production and utilization sector.

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INTRODUCTION

Portland cement is among the most consumed ingredient in concrete production and is a commonly utilized substance in the construction industry. Nevertheless, the Portland cement manufacturing process is characterized by its vast natural resource consumption, energy intensiveness, and a large amount of CO2 releases though. For instance, a single tone of Portland production requires approximately 4GJ of energy, emits around 1.25 tons of CO_2, and consumes more than 1.7 tones of virgin materials [1-2]. Hence, we need to look for alternative construction inputs.

Geopolymer cement is considered to be an environment-friendly alternative material to Portland cement. Alkali-activated silicium-aluminium materials are produced by mixing siliceous-aluminum enriched materials with alkali activators [3]. Furthermore, the water needed to synthesize geopolymers is comparatively lower; less energy is required for the manufacturing of geopolymers in comparison to conventional cement. On top of this, geopolymers are known for their excellent heat resistance, bond strength, and resistance to harsh environments [4-6]. As a result, these materials are gaining the considerable attention of several scholars in many countries.

On the other hand, in recent days, the amount of construction and demolition waste is rising throughout the world. However, the rate of increase differs from country to country. For instance, reports cited that the USA construction sector produces more than 100M tonnes of construction and demolition wastes annually [7]. On the other study, the amount of only demolished concrete each year in the same country is estimated to be approximately 50 million tons [8]. However, in the European countries, this figure rose by around 10 million tons of destructed concrete [8]. To save the natural ecosystem from exhausting natural aggregate, aggregates from construction and demolition wastes have been employed to manufacture concrete [9]. Recycled coarse aggregate contains natural aggregate and old attached mortar. RCA has a couple of interfacial transition zones, i.e., new cement paste, and the other is with an old cement-sand matrix. As a result, the geopolymer concrete obtained from RCA develops a more complex structure than concrete produced from the natural coarse aggregate. Old interfacial transition zone experiences micro-cracks that reduce the performance of the resulting concrete matrix. In addition, RCA consumes more water than virgin aggregate. According to Etxeberria et al. [10], the concrete obtained from recycled coarse aggregate consumed at least 5% more water to gain similar workability properties with concrete produced from the natural aggregate.

On the other hand, Mahdieh et al. [11] explored the interfacial performance between fly ash paste and recycled aggregate concrete with the aid of a laser scanning microscope (LSM) and Energy dispersive spectroscopy (EDS). The observation indicated that both new and old interfaces in fly ash-based geopolymer concrete with recycled aggregate were found dense. The prior incomplete interphase of re-used aggregate particles inside the recycled aggregates geopolymer concrete was not porous, which was not seen in the case of conventional concrete with the same aggregate. The mixture of fly ash-based geo-polymer with recycled aggregate is considered a suitable combination with improved engineering properties that can head to environmentally friendly construction input.

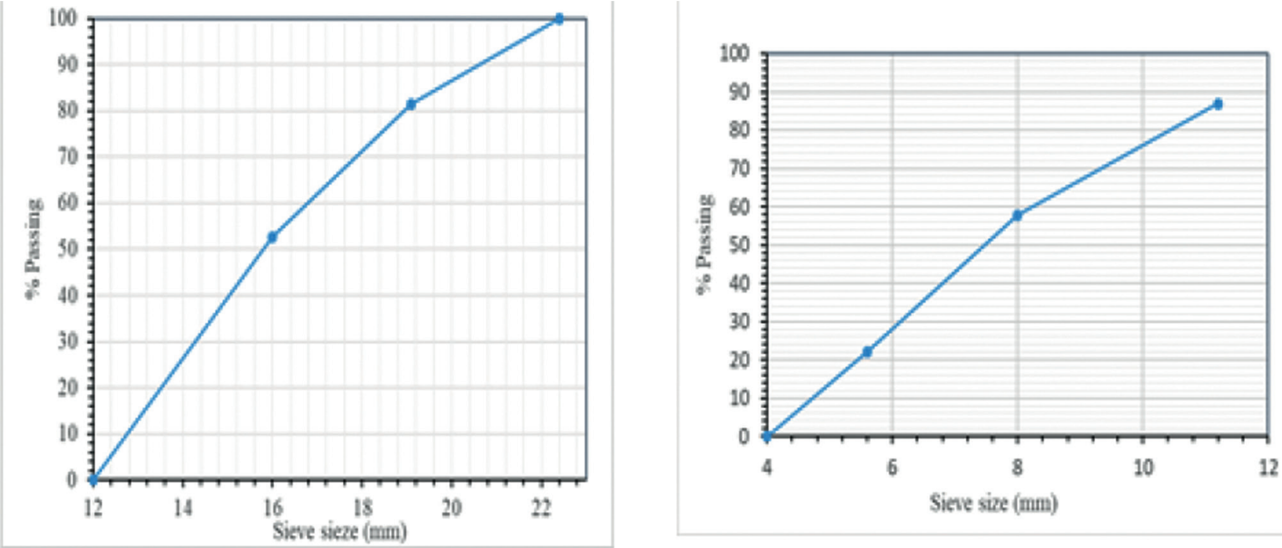
In the study done by Naga et al. [12], the mechanical performance of geopolymer concrete with the recycled aggregate proportion of up to 40% has shown only a slight reduction with the increase of recycled aggregate ratio. Whereas the decrement rate after 40% replacement was adverse, limiting the concrete's usability for the structural applications.

Mesgari S. et al. [13] found that the partial replacement of coarse natural aggregate with recycled geopolymer concrete aggregate ratio of up to 20% has caused an insignificant change in the modulus of elasticity, flexural strength, and volume of permeable voids of OPC concrete. Hasan et al. [14] revealed the applicability of natural and recycled coarse aggregates in structural concrete. The results indicated that both compressive strength and splitting tensile strength of concrete saw reduction with the increase of recycled coarse aggregate. However, the concrete sample produced from 100% RCA showed greater splitting tensile strength than 50% RCA concrete. Also, the inverse relation between RCA and workability of concrete was observed in this study.

This piece of study targets to investigate the characteristics of geopolymer concrete containing recycled concrete aggregate and steel fiber additives. The geopolymer concrete specimens were produced from low calcium fly ash, ground granulated slag, NaOH, Na_2SiO_3, superplasticizer, sand (an equal share of natural river sand and crushed limestone sand), and with partial replacement of natural aggregate with recycled aggregate.

MATERIALS AND METHOD

In this study, low calcium fly ash from Çatalağzı Thermal Power plant, Çatalağzı, Turkey with a specific gravity of 2.37, the chemical makeup of 58.75% SiO_2, 25.24% Al_2O_3, 5.76% Fe_2O_3, and 1.46% CaO, and granulated blast furnace slag with the chemical composition of 40.55% SiO_2, 35.58% CaO, 12.83% Al_2O_3, and 5.87% MgO were utilized as a base material (please include PSD of FA and GBFS, if available). Na_2SiO_3 with 11.5% Na_2O, and 22.5% SiO_2, and NaOH with concentrations of 13 M were employed alkali activator solutions. To maintain the workability of the resulting mixture a carboxylic ether polymer with long side chains in liquid form was used. Natural river sand and crushed sand with a specific gravity of 2.7 and 2.65, respectively, were employed in this study. The maximum nominal diameter of fine



a) *Particle size distribution of NO II RCA*

b) *Particle size distribution of NO I RCA*

Figure 1. Particle size distribution of RCA.

aggregates and coarse aggregates were 4mm and 22mm, respectively. The two types of coarse aggregates identified as natural limestone and recycled coarse aggregate (one to one ratio of NO-I and NO-II RCA) obtained from demolished buildings nearby Istanbul were used in this experimental work. The specific gravity of natural limestone and recycled coarse aggregate were 2.71 and 2.57, respectively. The water absorption capacity of recycled and natural coarse aggregates was evaluated as 6.8% and 1.2%, respectively. The recycled coarse aggregate possessed higher water absorption capacity due to adhered mortar and some other possible impurities on its surface. Also, the particle size distribution of RCA is given in figure 1. The crimpled steel fiber with an aspect ratio of 20 (50mm length and 2.5mm diameter) and tensile strength of 800 MPa was used in the study.

Mix Proportions and Sampling

Table 1 illustrates the mixed proportion of the concrete mixtures used in this experimental work. Chemical solutions to binder ratio of 0.45 and sodium silicate to sodium hydroxide ratio of 2.5 by mass were implemented for every mix. The proportion of steel fiber was adjusted to 0.3% by volume.

Firstly, dry ingredients, including binders, were mixed for 1 min, and then chemical solutions were added and mixed for another 2 minutes. Next, the mixer was paused, and steel fibers were evenly dispersed throughout the mix. Finally, superplasticizer and extra water were poured and mixed for extra 2 minutes. The addition of superplasticizer and extra-water enhanced the workability and flowability of the fresh concrete.

After mixing, cylindrical specimens with 100 mm diameter and 200 mm height and 71×71×71 mm3 cubes were cast for splitting tensile strengths and abrasion resistance test. In addition, 100×100×100 mm3 and 100×100×500 mm^3 samples were used for compressive and flexural strength tests, respectively. And then, the specimens were covered with plastic sheets and left standing for 24-hour indoor temperature, and then they were demolded and kept in 23°C and 60% relative humidity-controlled room until the age of 1 year to determine long-term strength properties and abrasion resistance of the specimens.

Compressive strength test was conducted after 56 and 365 days in compliance with the test procedure given in EN 12390-3 [15]. A splitting tensile strength test was performed according to the splitting tensile strength test procedure stated in ASTM C496 -11 [16]. A flexural strength test was performed after 56days and 1 year of curing period according to ASTM C1609 [17] standard procedure. Whereas, Böhme test EN13892-3 [18] procedure was used to perform the abrasion resistance test of the specimens. The concrete samples were centrally loaded with a 294±3 N load. Each specimen was tested for 16 cycles, each consisting of 22 revolutions. The grinding path of the disc, evenly strewn with 20 g of the standard abrasive powder, rotates at a speed of 30rpm. The thickness of the sample was measured using a thickness measuring instrument from six points at the end of each cycle. Also, the resulting loss in mass of the specimen was evaluated, to determine the abrasion loss of the concrete, using the weight of the specimen before and after each test. The abrasion thickness loss was evaluated after 16 cycles using the formula indicated in equation 1.

$$t = \frac{M1 - M2}{M1} * \frac{V}{A} \quad (1)$$

Where,
t : Wear thickness due to abrasion (mm)
M1: The specimen's mass before the test (g)
M2: The specimen's mass after the test (g)
A: Surface area of the specimen (mm^2)
V: Volume of the specimen (mm^3)

RESULTS AND DISCUSSION

Fresh Properties of Concrete

The workability of the resulting geopolymer concrete is determined just after mixing. Also, the flow ability and viscosity of the matrix were observed during the mixing and casting of the concrete. The slump height was decreased with the increase of recycled aggregate proportion. The magnitude of the slump was recorded in the range of sixteen to twenty centimeters. No significant segregation was observed while conducting the slump test. As inspected from the fresh characteristics of the resulting concrete matrix the flowability and workability of the geopolymer concrete declined with the rise of recycled aggregate ratios. This is due to the higher water absorption capacity of recycled aggregate and the ability of microfibers to hinder the flowability of the concrete matrix.

Compressive Strength

The given figure 2 presents the 56 and 365 days compressive strength results of geopolymer concrete samples produced with the combination of recycled coarse aggregate and steel fiber.

Overall, both short and long-term compressive strength results experienced a decrease and increased with the rise of recycled aggregate ratio. On the other hand, all specimens' 56 days and 1-year strength results do not exceed 27 and 33.2 MPa, respectively.

The 1-year average compressive strength of concrete samples produced using natural coarse aggregate only (CS3R0) stood at 29.6 MPa, slightly higher than 56 days strength for that mix design. However, incorporating 10% recycled coarse aggregate (CS3R10) dropped by around 14%, which was still higher than the 56-day figure at the same proportion of recycled aggregate. For the next series of the mixture (CS3R20), the figure gradually rose to 33.2 MPa, which is the highest compressive strength result ever recorded in this series of mixtures. From here on, the specimens started a consistent decrease in compressive strength, resulting in a magnitude slightly higher than 21 MPa for the mix design identified as CS3R40. This was also the lowest magnitude of a 1-year strength results out of the five series of mix designs.

The 56 days compressive strength results showed the same trend as that of 365 days outcomes. Beginning in a 0% recycled aggregate ratio, the magnitude of the specimen's compressive strength stood at 24 MPa. This was reduced to around 20 MPa with the addition of 10% re-used coarse aggregate into the geopolymer concrete mix design. Then in the following series of the mixture (CS3R20), this number has grown to 27 MPa, slightly lower than a year old concrete sample's compressive strength result. Finally, by increasing the recycled aggregate ratio to 40% (CS3R40), the magnitude of compressive strength reduced to 17 MPa, around 20% below the compressive strength of the same concrete sample at the age of one year.

In conclusion, the compressive strength of the geopolymer concrete samples decreased with the increase of recycled coarse aggregate ratio. However, up to a 20% re-used aggregate amount does not significantly reduce the strength results. On the other hand, the recycled aggregate ratio of 40% saw a strength loss of around 29% compared to that of the specimens produced entirely from the natural coarse aggregate. Recycled coarse aggregate possesses a porous structure because of the attached mortar and absorbs more water, which affects its strength and results in a drop in compressive performance of the resulting concrete matrix [19, 20]. Also, impurities such as adhered mortar reduce the density of recycled coarse aggregate, which makes it weaker

Table 1. The mix proportion used (kg/m^3)

Mix Label	FA	Slag	NCA	RCA	Sand	NaOH	Na_2SiO_3	SP	EW	Steel fiber (By volume)
CS3R0	90	69	1115	0	743	51.18	127.92	15.22	30.4	0.3%
CS3R10	90	69	1003	112	743	51.18	127.92	15.22	30.4	0.3%
CS3R20	90	69	892	224	743	51.18	127.92	15.22	30.4	0.3%
CS3R30	90	69	780	336	743	51.18	127.92	15.22	30.4	0.3%
CS3R40	90	69	669	448	743	51.18	127.92	15.22	30.4	0.3%

FA: Fly Ash; NCA: Normal Concrete Aggregate; RCA: Recycled Concrete Aggregate than the virgin aggregate. The inverse relation between recycled coarse aggregate proportion and compressive strength was demonstrated in the other studies [20, 21].

Splitting Tensile and Flexural Strength

The splitting tensile and flexural strength results are displayed in Fig. 3 and 4. The replacement of natural coarse aggregate with recycled aggregate, up to 30%, does not reveal a considerable effect on specimen splitting tensile and flexural strength. On top of these, the age of concrete samples does not cause a remarkable impact on the strength of samples. The 56 days and 365days of the splitting tensile strength, at a given steel fiber ratio, were reduced up to 31% and 24%, respectively, with the incorporation of NCA with RCA at 40%. Furthermore, the strengths of mixes containing steel fibers, except for the tensile strength of CS3R20, were lower than that of the control mix. This may be attributed to the RCA concrete being feeble in the fracture plane due to the porous microstructure in the existence of re-used aggregate. However, in some cases, the mixtures with a high proportion of RCA may have better tensile strength results due to suitable physical characteristics of recycled aggregate and an excellent interfacial bond between aggregate and cement-sand matrix. Especially, GGBS can create dense microstructural properties with recycled aggregate by filling voids on the surface of aggregates [22].

The 56 days and 365days of the flexural strength, at a given steel fiber ratio, were declined up to 35.9% and 34.5%, respectively, with the incorporation of NCA with RCA at 40%. In general, both flexural and splitting tensile strength decreased with the rise of recycled aggregate ratio. The existence of this pattern may be due to RCA application, which leads to a less dense interfacial transition zone between a new fly ash/slag geopolymer mortar and an old attached

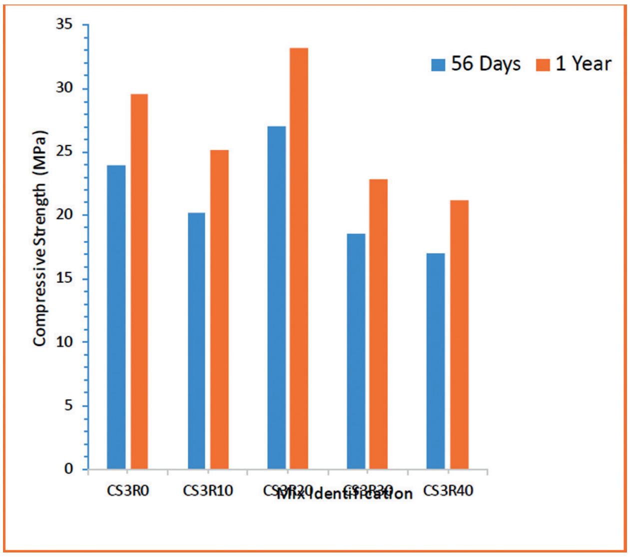


Figure 2. The 56 and 365 days compressive strength results.

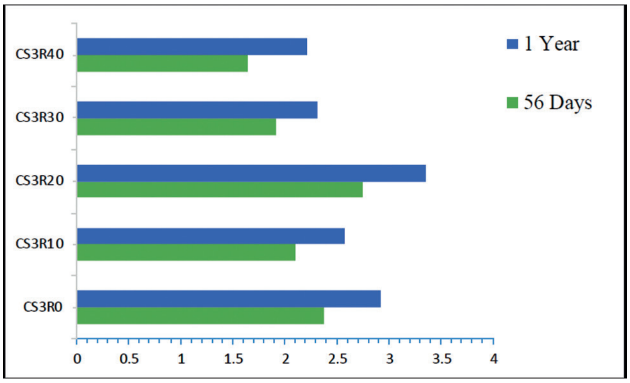


Figure 3. The 56 and 365 days splitting tensile strength results.

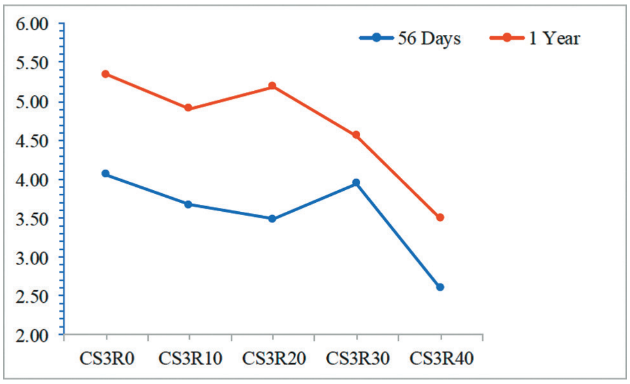


Figure 4. The 56 and 365 days flexural strength test results.

Table 2. Average wear thickness and percentage weight loss from abrasion resistance test

Mixture Label	Initial Weight (g)	Final weight (g)	Loss in weight (%)	Average wear thickness (mm)
CS3R0	820.9	802.8	2.20	0.23
CS3R10	797.3	769.2	3.52	0.53
CS3R20	811.1	786.5	3.03	0.33
CS3R30	798.8	762.3	4.57	0.74
CS3R40	794.4	744	6.34	0.96

mortar. These results are consistent with the study by Rahal [23] and Nuaklong et al [21].

Abrasion Resistance Test

The results of abrasion resistance are given in Table 2. A lower percentage of mass loss and average wear thickness represents the better abrasion resistance of geopolymer concrete samples. Both weight loss and wear thickness increased in proportion to the amount of recycled coarse aggregate. Moreover, the highest mass loss and wear thickness values were recorded as 6.34% and 0.96mm, respectively, with NCA substituting with RCA at 40%. This reflected that the utilization of recycled aggregate in fly ash/slag-based geopolymer concrete gave lower abrasion resistance than that of natural aggregate. The trend of outcome was similar to the results of compressive and splitting tensile strength.

CONCLUSION

In this experimental work, the potential applicability of the recycled coarse aggregate for the partial replacement of natural coarse aggregates in concrete was assessed, and the possible outcomes of the various proportion of RCA were recorded. Generally, the following conclusions can be drawn from this experimental work:

The workability of the concrete dropped with the rise of recycled coarse aggregate proportion; the reduction in a slump increased in line with the recycled aggregate ratio. The compressive strength of the concrete was negatively affected by the incorporation of recycled coarse aggregate. The 56 and 365 days compressive strength of the samples produced with only NCA recorded 24MPa and 29.58MPa, respectively. The ultimate drop in 56 and 365 days compressive strength for 40% RCA was 29% and 28%, respectively. The maximum reduction in compressive strength for 10% and 30% RCA was 16% and 23%, respectively. The 1-year splitting tensile strength of 0%, 10%, 20%, 30% and 40% RCA was recorded as 2.92MPa, 2.57Mpa, 3.35MPa, 2.31MPa and 2.22 MPa, respectively. The splitting tensile strength of all specimens was increased with age from 56 days to 365 days. Also, flexural strength results followed approximately the same pattern as that of splitting tensile strength results. The magnitude of flexural strength reduced with the rise of RCA content. In terms of abrasion resistance, all specimens, irrespective of recycled aggregate amount, gave promising results. However, due to the abrasion effect, both weight loss and wear thickness were slightly increased with RCA content. The maximum weight loss and abrasion thickness were recorded for mixtures made from 40% RCA i.e., 6.34% and 0.96mm, respectively. The study showed that ideal outcomes for the compressive performance, splitting tensile strength, and abrasion resistance test was obtained for up to 20% RCA incorporation. The RCA ratio of up to 20% was considered the optimum proportion due to the lower reduction rate than the control mix for the splitting tensile strength, flexural strength, compressive strength, and abrasion resistance test. Furthermore, the utilization of RCA helps to reduce the depletion of natural coarse aggregate. Extraction of natural aggregate by itself is expensive and consumes a significant amount of resources. Also, recycling construction and demolition wastes reduce the area of land reserved for landfills. As a result, the use of recycled coarse aggregates in concrete production gives significant environmental benefits without harming the peculiar engineering properties of the concrete structures.

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AUTHORSHIP CONTRIBUTIONS

Authors equally contributed to this work.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

REFERENCES

[1] Wilson A. Cement and concrete: Environmental considerations. Environ Build News 1993;2:1.

[2] Mehta KP. Reducing the environmental impact of concrete. Concr Int 2001;23:61–66.

[3] Davidovits J. Geopolymers. J Therm Anal 1991;37:1633–1656. [CrossRef]

[4] Zhao R, Sanjayan JG. Geopolymer and Portland cement concretes in simulated fire. Mag Concr Res 2011;63:163–173. [CrossRef]

[5] Temuujin J, Minjigmaa A, Lee M, Chen-Tan N, van Riessen A. Characterisation of class F fly ash

geopolymer pastes immersed in acid and alkaline solutions. Cem Concr Compos 2011;33:1086–1091. [CrossRef]

[6] Sarker PK. Bond strength of reinforcing steel embedded in fly ash-based geopolymer concrete. Mater Struct 2011;44:1021–1030. [CrossRef]

[7] Mills TH, Showalter E, Jarman D. A cost-effective waste management plan. Cost Engineering (Morgantown, West Virginia) 1999;41:35–43.

[8] Kawano H. The state of using by-products in concrete in Japan and outline of JIS/TR on recycled concrete using recycle aggregate. Proceedings of the Ls, Fib Congress, Session, 10, 2002.

[9] Li, X. Recycling and reuse of waste concrete in China: Part I. Material behaviour of recycled aggregate concrete. Resour Conserv Recycl 2008;53:36–44. [CrossRef]

[10] Etxeberria M, Vázquez E, Marí A, Barra M. Influence of amount of recycled coarse aggregates and production process on properties of recycled aggregate concrete. Cem Concr Res 2007;37:735–742. [CrossRef]

[11] Khedmati M, Kim Y-R, Turner JA. Investigation of the interphase between recycled aggregates and cementitious binding materials using integrated microstructural-nanomechanical-chemical characterization. Compos Part B Eng 2019;158:218–229. [CrossRef]

[12] Naga Sai A, Kishore PPV. An experimental study on strength properties of concrete using recycled aggregate as replacement in coarse aggregate. Int J Res Appl Sci Eng Technol 2018;6:665–676. [CrossRef]

[13] Mesgari S, Akbarnezhad A, Xiao JZ. Recycled geopolymer aggregates as coarse aggregates for Portland cement concrete and geopolymer concrete: Effects on mechanical properties. Construct Build Mater 2020;236:117571. [CrossRef]

[14] Ahmed M, Akter A, Islam MT, Roy S, Haque M, Imam Hasan M. Experimental review for suitability study of natural coarse aggregates (stone chips) and recycled coarse aggregates in structural concrete. Int Res J Eng Technol 2019;6:1469–1473.

[15] British Standard Institution BS EN 12390-3:2019, Testing hardened concrete Compressive strength of test specimens., London, 2009.

[16] ASTM C496-11,. Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens, Annu. B. ASTM Stand. 2011; 04.02, 1–5.

[17] ASTM International. C1609/C1609M-12, Standard Test Method for Flexural Performance of Fiber-Reinforced Concrete (Using Beam with Third-Point Loading), West Conshohocken, PA, 2012.

[18] European Standard EN 1338. Concrete Paving Blocks - requirements and test methods, 2003.

[19] Hansen TC, (ed). Recycling of Demolished Concrete and Masonry. Boca Raton, Florida: CRC Press, 2014.

[20] Katz A. Treatments for the improvement of recycled Aggregate. J Mater Civil Eng 2004;16:597–603. [CrossRef]

[21] Nuaklong P, Sata V, Chindaprasirt P. Influence of recycled aggregate on fly ash geopolymer concrete properties. J Clean Prod 2016;112:2300–2307. [CrossRef]

[22] Saludung A, Ogawa Y, Kawai K. Effect of GGBS addition on properties of fly ash-based geopolymer at high temperatures. Concrete Eng Ann Proceed 2019;41:1991–1996.

[23] Rahal K. Mechanical properties of concrete with recycled coarse aggregate. Build Environ 2007;42:407–415. [CrossRef]