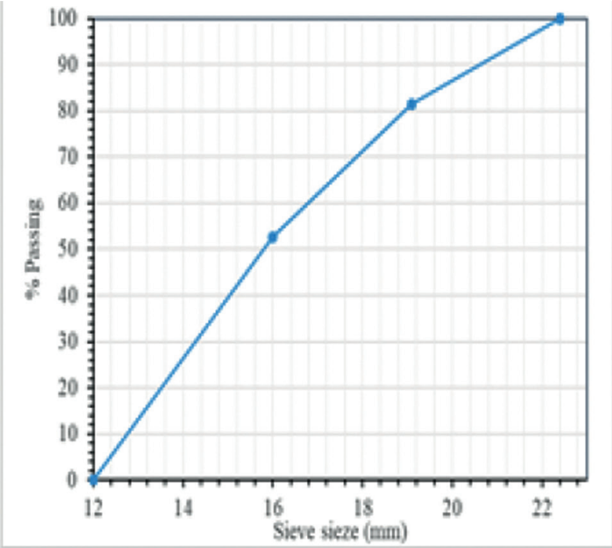
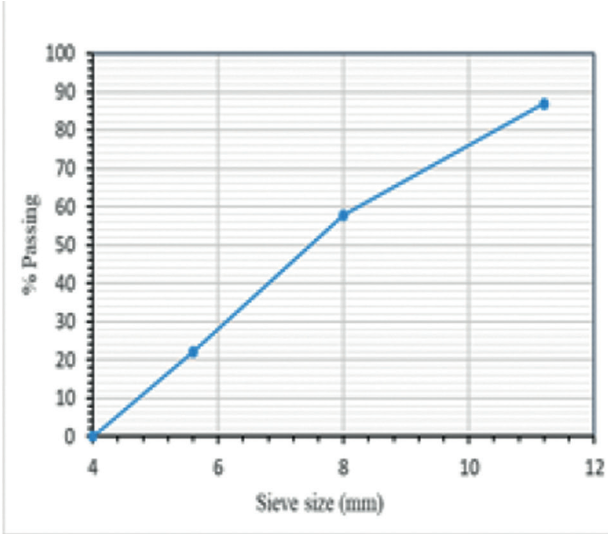


a) *Particle size distribution of NO II RCA*



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

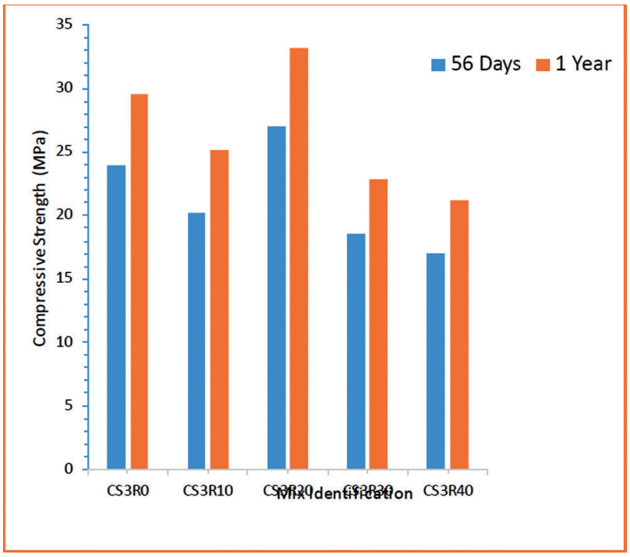


Figure 2. The 56 and 365 days compressive strength results.

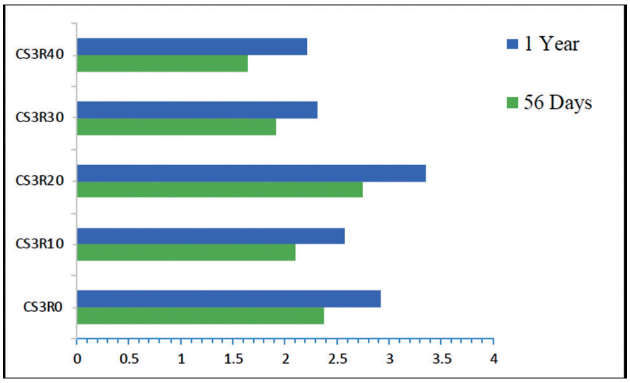


Figure 3. The 56 and 365 days splitting tensile strength results.

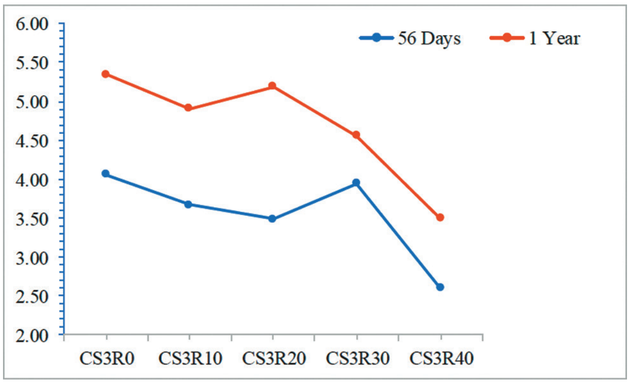


Figure 4. The 56 and 365 days flexural strength test results.

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

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]