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Effects of Forest and Glass Industry Waste on Mechanical Properties of Geopolymer Concrete and Cost Analysis

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Abstract - *Forest industry waste ash (FIWA), which is defined as a renewable energy source and sustainable material, is released as a result of energy production and it is known that waste ash contributes to strength and durability properties by using it in concrete production. In addition, waste glass is another waste material that is produced in large quantities and is difficult to dispose of. It is known that most of the waste glass is collected, remelted and used in the production of new glass. When waste glass is used to micro size, it undergoes pozzolanic reactions with cement hydrates to form secondary Calcium-Silicate-Hydrate (C–S–H). The resulting paste has stronger C-S-H property than ordinary cement paste. This micro-filling effect of glass powder makes it a material that reduces the permeability of concrete and affects the adhesion of concrete to aggregate better than normal conventional concrete. Aim of work; geopolymer concrete to be produced with FIWA and GP of different properties was investigated. FIWA and GP were refined to a certain degree and used in the production of geopolymer mortars at 0%, 10% and 15% ratios instead of ground blast furnace slag (GGBFS). The samples were kept in steam curing for 6h, 12h and 24h. The test results showed that the curing time of 12 hours had a positive effect on the compressive strength, and the curing time of 24 hours was effective in the bending strengths. It has been seen that the obtained geopolymer production costs can be used as an alternative to conventional concrete.*

Key Words: Geoplymer concrete, Compressive strength, NaOH, Na_2SO_3, Cost analysis

1.INTRODUCTION

More than 1 m^3 of concrete is produced per person in the world every year and Portland cement is generally used as a binder in these concretes [1] . The amount of cement used corresponds to approximately 4,1 billion tons/year [2]. It is estimated that for every 1.5 tons of cement produced, approximately 1.0 tons of CO_2 will be released into the atmosphere (Fig. 1) [3,4]. Considering this ratio, it is predicted that approximately 3-5% of the CO_2 emissions in the world will be realized by the total cement production [5]. The use of mineral additives in concrete production is gaining importance day by day in reducing this effect and other negative effects that may harm the environment. Today, sustainable materials that can meet the increasing need for cement by emitting less CO_2 into the atmosphere are being researched as an awareness. In addition, the use of industrial production by-products, which are either waste or by-products, in alternative methods provides a perspective on the researched issues. This growing global awareness of environmental issues may explain the interest in the use of alternative and renewable energy sources.

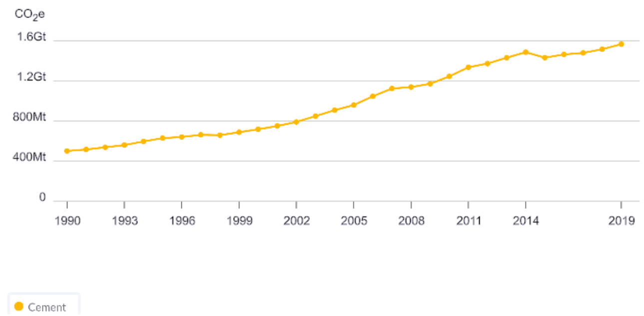


Figure 1. Global historical CO_2 emissions [19-20]

In addition, the problem of accumulation of waste is increasing worldwide, especially in densely populated areas. Most of these materials are left as stock, storage material or dumped in selected areas [6]. Industrial by-products such as fly ash, silica fume and glass waste are used in concrete instead of cement [7] . In addition, studies on the use of wastes such as agricultural waste products [8] such as rice husk ash or wood ash from forest industry production have gained importance. Replacing certain proportions of wood ash with cement in concrete mixes not only reduces cement consumption, but can also benefit the durability properties of concrete. At the same time, they increase the late strength of concrete by showing pozzolanic properties. However, depending on the replacement ratios used, it may also cause some reductions in the early strength of the concrete . In addition to its use as a building material instead of cement used in the production of cement-based materials, wood ash (FIWA), which has pozzolanic properties and an important potential as an activator, can also be used [9]. A high percentage of wood waste is generated in facilities producing wood-based materials [5]. However, the use of wood ash (FIWA) is limited to normal strength concretes due to its carbon content [9].

Geopolymer concrete, on the other hand, is a type of inorganic polymer formed by the interaction of calcium (Ca) and alumina (AL) rich solids with a highly alkaline solution such as sodium hydroxide and sodium silicate [10] , which combines the properties of polymers. It is environmentally friendly and requires moderate energy in its production [11–14].

In this study, forest industry wastes and glass waste dust obtained from SFC Kastamonu facility were substituted for slag in geopolymer mortar in certain proportions and production costs were compared.

2. MATERIALS AND METHODS

2.1 Materials

2.1.1 Ground Granulated Blast-Furnace Slag (GGBFS)

In this study, the GGBFS was provided from the Ereğli Iron–Steel Factory (Oyak) in Turkey with a specific gravity (S.G) of 2.81 g.cm^{-3} and a fineness of 4250 cm^2.g^{-1}. The chemical composition is shown in Table 1.

Table 1. The chemical composition of GGBFS, GP and FIWA (%)

	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	K_2O	Na_2O
GGBFS	36.7	5.2	0.98	32.61	10.12	0.99	0.76	0.42
FIWA	28.86	9.65	3.82	45.55	5.13	3.21	2.77	1.44
GP	72.66	1.57	0.39	11.41	1.24	0.07	0.54	12.89

2.1.2 Forest Industry Waste Ash (FIWA)

In this study, forest industry waste and glass waste dust obtained from the SFC Kastamonu facility were substituted in certain proportions instead of slag in the geopolymer mortar. Table 1 shows the chemical properties of the FIWA. The value of CaO content is less than 50%, while the value of SiO_2 + Al_2O_3 +Fe_2O_3 exceeds 70 %. Since the FIWA's fineness was sufficient, it was first sieved through a 0.125 mm sieve and FIWA was used.

2.1.3 Waste Glass Powder (GP)

Table 1 shows the chemical composition of the glass powder. The value of CaO, Na_2O contents are about 11% and 13%, respectively, while the value of SiO_2 + Al_2O_3 +Fe_2O_3 exceeds 70 %. A losangles machine is used to waste glass grounded, which to produce finer ash, will be grounded by a small mill. The mean diameter of the particle size is 13 µm at a density of 2.56 g.cm^{-3} and a fineness of 5320 cm^2.g^{-1}.

2.1.4 Standard Aggregate

Table 2 shows the sieve analysis produced by Trakya Cement. All the aggregate was used standard aggregate in accordance with the TS EN 196-1 at the maximum size of 2 mm.

Table 2: Sieve analysis

Size of sieve (mm)	Remaining cumulative (%)
2.0	0
1.6	7±5
1.0	33±5
0.5	67±5
0.16	87±5
0.08	99±1

2.1.5 Alkali activator

Sodium Hydroxide (NaOH) with a molar mass of 40 g.mol-1, a density of 2.13 g.cm^{-3}, a white color and a purity of 97% in solid form, and a content of 8.5-9.2% Na_2O and 30% SiO_2 in liquid form. Sodium silicate (Na_2SiO_3) with mole ratio ≤3.3 was used.

2.2 Methods

2.2.1 Preparation of Specimen Mixtures

The aim is to investigate blended GGBFS, GP and FIWA geopolymer mortars with a water ratio (W/B) of 0.37 to the binder. In conformity with TS-EN 196-1, the standard aggregate, GGBFS, GP, FIWA, water, Na_2SiO_3, and NaOH are used in the production of these geopolymer mortars. NaOH pellets in 1 liter of water should be dissolved by adding water in a certain volume bottle and the alkali activator should be prepared by the combination of NaOH concentration and Na_2SiO_3 mixtures used, before mixing with other compounds 24 hours should be rested. In this study, the same method was used in the preparation of NaOH solution in mixtures. In order to dissolve NaOH in pellet form in 1 liter of water, molality calculation was taken into account. For this purpose, a certain weight of NaOH was added to this water and the mixture was obtained in the corresponding molalite. For this purpose, NaOH, which is 640 g for 16 molality, was dissolved in 1 liter of water and kept for 24 hours as NaOH is a material that increases the geopolymerization process. And also the ratio of sodium silicate to sodium hydroxide (Na_2SiO_3: NaOH =1) was fixed as to equal. In addition, the amount of the binder GGBFS+FIWA+GP is kept constant at an 730g/900g standard aggregate. Table 3 and Table 4 reveals the ingredients of the mortar mixtures. The specimens were immersed in steam cured (SC), that is the series, the specimens were SC at 85°C for a period ranging from 6 to 24 hours.

Table 3. Mortar mixture design

Group	GGBFS (%)	GP (%)	FIWA (%)	Cure hours
REF	100	0	0	6
S1	90	10	0	6
S2	85	15	0	6
S3	80	10	10	6
S4	70	15	15	6
S5	90	10	0	12
S6	85	15	0	12
S7	80	10	10	12

S8	70	15	15	12
S9	90	10	0	24
S10	85	15	0	24
S11	80	10	10	24
S12	70	15	15	24

Table 3. Mortar mixture ingredients (g/dm^3)

Mix	W/B	GGBFS (g)	FIWA (g)	GP (g)	Agg. (g)	NaOH (g)	Na_2SiO_3 (g)	Water (g)
Ref	0,35	730	0	0	900	146	146	108
S1-S5-S9		656,55	0	72,95				
S2-S6-S10		620	0	109,18				
S3-S7-S11		583,6	72,95	72,95				
S4-S8-S12		570,65	109,18	109,18				

2.2.2 Casting of the Specimens

Table 3 shows the mix proportions as a predefined order, followed by mixing in a Hobart mixer. For the purpose of gaining added homogeneity to allow smooth SiO_2 and NaO_2 release in the mortar, the water and sodium Hydroxide were combined in a glass jar up to the point of their complete dissolution. The mixing process is shown in Fig 1.

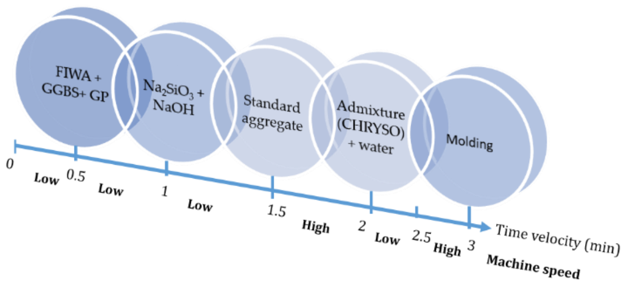


Figure 1: Steps of concrete mixing

3. RESULTS AND DISCUSSION

When the geopolymer concretes are examined (Fig. 2), it is seen that the reference sample can reach 17.5 MPa compressive strength and 1.6 flexural strength after 6 hours of curing when GP and FIWA are not used, while these values reach 51 MPa compressive strengths and 1.8 flexural strengths, respectively, in the use of GP and FIWA. This increase in strength with increasing curing time resulted in 77 MPa compressive strength and 2.15 flexural strength in 12 hour curing time, and 75 MPa compressive strength and 3.01 flexural strength in 24 hour curing.

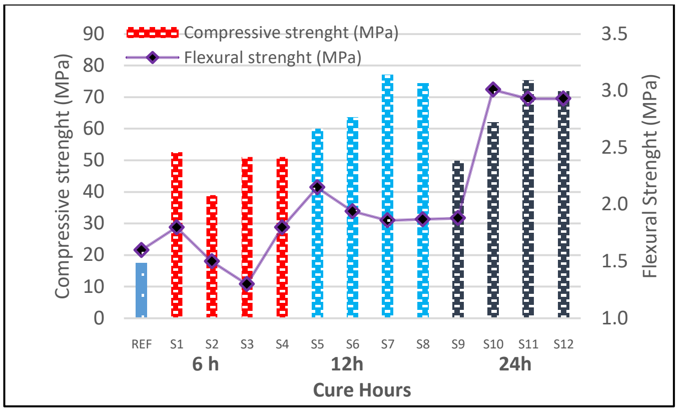
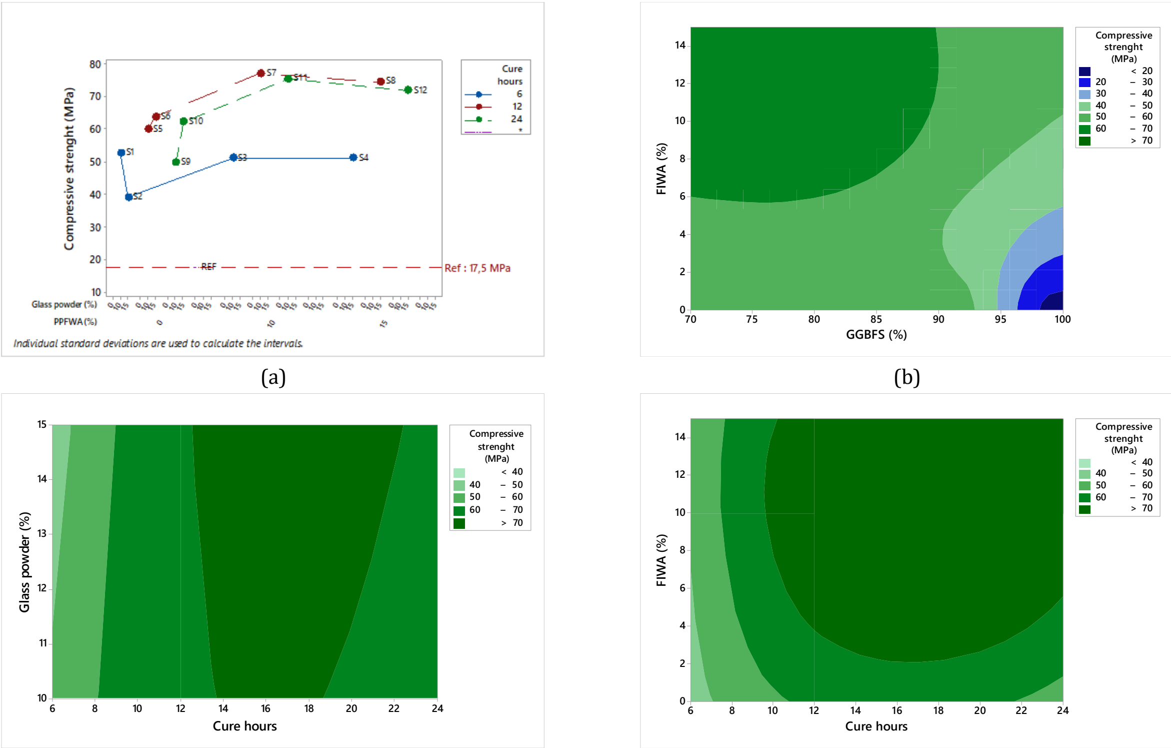


Figure 2. Changes in strength of geoplimer concretes

When the effects of GP additive on the strengths is examined at Fig. 3 and Fig. 4, when no glass powder is used, the strength is 17.5 MPa after 6 hours of curing (Fig 3a; Fig. 4a), while the increase in strength has reached 52.5 MPa with an increase of approximately 3 times with the use of GP. The strength increased by about 10% according to the increasing glass powder ratio. This increase rate was highest in 10% GP use. When the effect of the FIWA additive is examined (Fig. 3b, Fig. 4b), it is observed that although there is a small decrease in strength when 10% is used, it causes an increase of approximately 10 MPa when 15% is used. In addition, 6 hours, which is the minimum curing time in FIWA usage, is insufficient for strength increase. The ideal time for compressive strength is minimum 12 hours, and it has been observed that the ideal curing time is 12 hours for its plus contribution to flexural strength. In other words, it was observed that the positive effect of increasing curing time on the strength did not increase in direct proportion to the increasing time, and 12-hour curing was sufficient for maximum strength (Fig 3c, Fig. 4d). In addition, it was observed that increasing glass powder caused an increase in curing times of 12 hours and above, and this increase occurred after 12 hours for compressive strength and after 24 hours for flexural strength (Fig 4c, Fig. 4d). This is due to the fact that the chemical bonds formed in geopolymer concretes, when suitable curing conditions are provided, take a more stable form and form a stronger bond.

Production costs for 1m^3 of Geopolymer concrete were investigated and the results are given in Table 6.

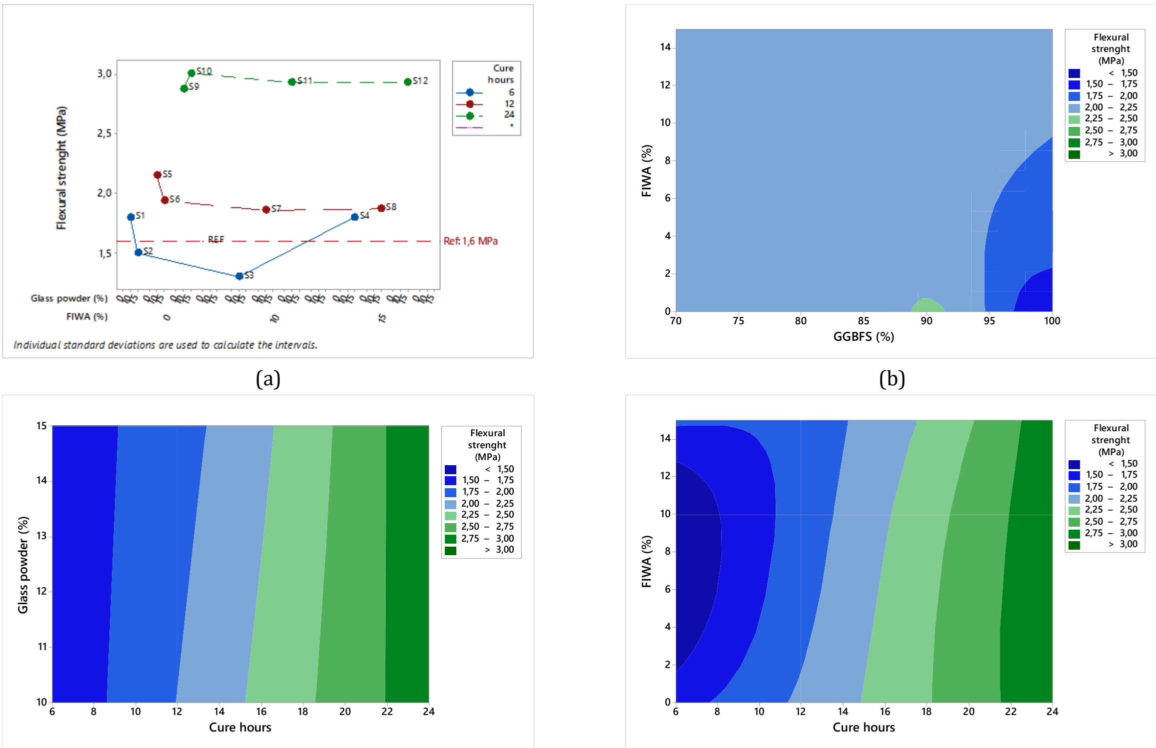
When Table 6 is examined, the production cost for 6 hours of curing is $137.69 when GP and FIWA are not used. Considering that there is a difference of approximately $2 per 1 m^3 in energy costs, geopolymer concrete costs have been calculated to vary between $149 and $162.



(a) (b)

(c) (d)

Figure 3. Effect of GP, FIWA and curing time on compressive strength at geopolymer concrete



(a) (b)

(c) (d)

Figure 4. Effect of GP, FIWA and curing time on flexural strength at geopolymer concrete

Table 6. Production cost ($) of 1 m³ geopolymer concrete as using material

Group	Type of mix	GGBFS	GP	FIWA	Aggregate	NaOH	Na_2SiO_3	Water	Energy	TOTAL*
REF	(100% GGBFS+0%GP+0%FIWA) + 6 h cure	36,50	0,00	0,00	21,6	40,88	37,96	0,095	0,66	137,69
S1	(90% GGBFS+10%GP+0%FIWA) + 6 h cure	32,83	18,24	0,00	21,6	40,88	37,96	0,095	0,66	152,26
S2	(85% GGBFS+15%GP+0%FIWA) + 6 h cure	31,00	27,30	0,00	21,6	40,88	37,96	0,095	0,66	159,49
S3	(80% GGBFS+10%GP+10%FIWA) + 6 h cure	29,18	18,24	0,66	21,6	40,88	37,96	0,095	0,66	149,27
S4	(70% GGBFS+15%GP+15%FIWA) + 6 h cure	28,53	27,30	0,98	21,6	40,88	37,96	0,095	0,66	158,00
S5	(90% GGBFS+10%GP+0%FIWA) +12 h cure	32,83	18,24	0,00	21,6	40,88	37,96	0,095	1,32	152,92
S6	(85% GGBFS+15%GP+0%FIWA) +12 h cure	31,00	27,30	0,00	21,6	40,88	37,96	0,095	1,32	160,15
S7	(80% GGBFS+10%GP+10%FIWA) +12 h cure	29,18	18,24	0,66	21,6	40,88	37,96	0,095	1,32	149,93
S8	(70% GGBFS+15%GP+15%FIWA) +12 h cure	28,53	27,30	0,98	21,6	40,88	37,96	0,095	1,32	158,66
S9	(90% GGBFS+10%GP+0%FIWA) +24 h cure	32,83	18,24	0,00	21,6	40,88	37,96	0,095	2,64	154,23
S10	(85% GGBFS+15%GP+0%FIWA) +24 h cure	31,00	27,30	0,00	21,6	40,88	37,96	0,095	2,64	161,46
S11	(80% GGBFS+10%GP+10%FIWA) +24 h cure	29,18	18,24	0,66	21,6	40,88	37,96	0,095	2,64	151,24
S12	(70% GGBFS+15%GP+15%FIWA) +24 h cure	28,53	27,30	0,98	21,6	40,88	37,96	0,095	2,64	159,98

* November 2021 market prices of cost calculations are used.

Table 7. Analysis of variance at geopolmer concrete

Source	DF	Adj SS	Adj MS	F-Value	P-Value
• **Regression**	5	507,412	101,482	125,55	0,000
• **Comressive strenght (MPa)**	1	2,443	2,443	3,02	0,126
• **Glass powder (%)**	2	203,559	101,780	125,92	0,000
• **FIWA (%)**	2	18,548	9,274	11,47	0,006
• **Error**	7	5,658	0,808		
• **Total**	12	513,070			

Geopolymer concrete production costs were compared with the costs of ready-mixed concrete plants produced with OPC (Fig. 5), and when the results were examined, it was seen that the concrete class (for ≥50 MPa) was insignificant for the production of high-strength geopolymer concrete at a significance level of $p<0.05$ (Table 7), and the use of GP and FIWA had a significant effect on the costs. When the sales prices of ready mixed concrete produced with OPC (Fig. 5) are analyzed, it is seen that it varies between \$60 and \$220 due to the high raw material costs on a country basis. However, with the increasing concrete strength with the use of GP and FIWA, it is at an acceptable level for the increasing costs of geopolymer concrete.

Table 8. Production regression equation for geopolymer concrete cost

GP (%)	FIWA (%)	Regreassion equation
0	0	Production cost ($)=136,90 + 0,0454 Comp. strenght
0	10	Production cost ($)=133,28 + 0,0454 Comp. strenght
0	15	Production cost ($)=134,92 + 0,0454 Comp. strenght
10	0	Production cost ($)=150,68 + 0,0454 Comp. strenght
10	10	Production cost ($)=147,07 + 0,0454 Comp. strenght
10	15	Production cost ($)=148,71 + 0,0454 Comp. strenght
15	0	Production cost ($)=157,88 + 0,0454 Comp. strenght
15	10	Production cost ($)=154,26 + 0,0454 Comp. strenght
15	15	Production cost ($)=155,90 + 0,0454 Comp. strenght

The compressive strength results obtained within the scope of this study were investigated for their usability in estimating costs, and the actual costs and the costs obtained statistically (Table 8, Fig. 6) were compared.

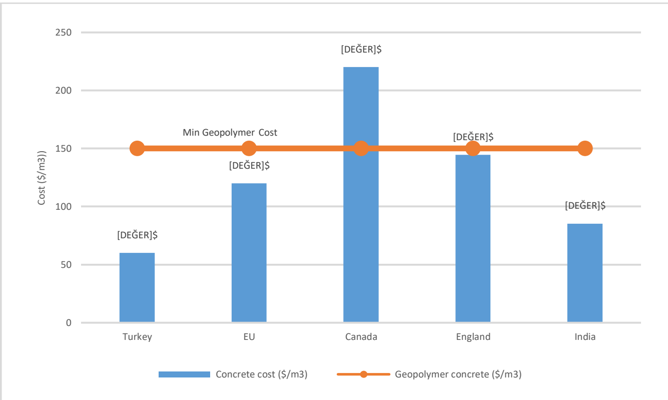


Figure 5. Ready mixed concrete sales prices in some countries (≥50 MPa) [15-18]

When figure 8 is examined, it has been determined that there is a statistically strong effect with R2=0.962 as a result of high strengths obtained for geopolymer concretes, and the actual cost can be calculated with the "compressive strength = 49,738.e0,0073cost " equation according to the compressive strengths. It has been determined that there is a strong relationship between the estimated costs obtained and the actual costs with R2=0.962441. These results show that there is no significant difference between the statistically obtained values and the actual values, and also the contribution of this study.

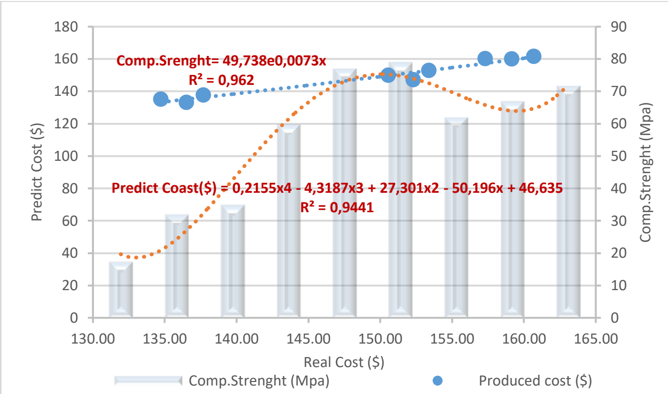


Figure 6. Variation of costs with strength

4. CONCLUSIONS

The experimental results led to the following conclusions:

- The results indicating that in this case, a 12-hour period is enough for steam curing at 85 °C.
- The high strength geopolymeric mortar with the compressive strength in the order of 77.07 MPa at 12 h can be obtained by activating GGBFS, GP, and FIWA blend with alkali activator cured at 85 °C stream curing.
- The flexural strength under steam curing condition at 85 °C, the 24-hours cured was higher than those under 6 h and 12 h.
- Geopolymer concrete production is costly compared to concrete produced with OPC. However, it has been observed that there is a concrete that needs to be deducted from the additional costs ($100/ton + $30 tax) to be incurred in the future in CO2 disposal.

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