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Effect of Class F Fly Ash on Strength Properties of Concrete

Anjeza Alaj [1], Visar Krelani [1*], Tatsuya Numao [2]

[1] *Civil Engineering and Infrastructure Department, University for Business and Technology, Pristina, Republic of Kosovo.*

[2] *Graduate School of Science and Engineering, Ibaraki University, Hitachi, Japan.*

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Abstract

Reducing the amount of CO_2 emissions in the environment is one of the priorities of the EPA and other environmental agencies. A way to reduce CO_2 emissions is by using fly ash in the concrete industry. Aside from environmental benefits, fly ash has numerous quality advantages; some of the positive effects were recognized earlier; however, in this research, the objective is to replace cement with a different percentage of class F fly ash with a low CaO content to produce sustainable concrete. Laboratory tests were performed to examine the rational percentage of cement replaced by class F fly ash in ordinary concrete C–25/30 and high-performance concrete C–50/60. In total, twelve different mix designs were prepared to examine consistency, setting time, shrinkage, and compressive strength in different periods of curing for more than 600 days. Using recycled material in new buildings still has some obstacles, but the future of construction must be green, so this research indicates that the objective of producing ordinary and high-performance concrete was achieved by replacing 30% of cement with class F fly ash.

Keywords: Fly Ash Class F; Ordinary and High-Performance Concrete; Compressive Strength; Shrinkage Sustainable Concrete.

1. Introduction

Producing eco-friendly concrete is a vital issue for civil engineering researchers, considering construction development and the demand for improving quality of life. CO_2 emissions contribute 65 percent to global warming, while 7–10% of CO_2 is generated only by producing cement. Furthermore, the construction industry has a very big impact on the environment by using natural resources and generating inert waste. So, developing further ways of producing sustainable buildings is the main issue of this century [1, 2]. Regarding its mechanical properties and long-lasting service, concrete is still considered the main material in the construction industry, and based on some research after water, concrete is the most widely used material, and in the coming years it is expected to increase usability [4–6]. So, producing eco-friendly concrete is the future of the construction industry. Considering the current situation, many countries are changing the industry of producing energy from gas to coal, so the amount of fly ash is going to increase constantly in the coming years, causing environmental damage and air and water pollution on a large scale [1, 3].

Fly ash as industrial waste is widely distributed around the world, and it doesn't have uniform properties that restrict its usability, such as chemical compositions and physical properties. A very common issue is that it often resembles properties of cement [7, 8]. Although much research has focused on using industrial waste on concrete, like metakaolin, rice husk, slag, etc. However, fly ash is the most widely used binder due to its easy availability and pozzolanic [9–11], but still, it is not investigated how the amount of fly ash content affects the production of specific concrete considering its properties.

* Corresponding author: visar.krelani@ubt-uni.net

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This research aims at assessing the potential reduction in CO_2 emissions associated with decreasing the amount of cement used in concrete by finding a rational amount of fly ash to replace it and produce environmentally friendly concrete. Inasmuch as fly ash resembles properties of cement, it is important to investigate different properties of concrete incorporating this quality of fly ash, such as improvements in workability, strength, drying shrinkage, setting time, and temperature rise. The physical properties and chemical compositions of fly ash change due to the type of coal composition and process of coal burned at a power plant. In this case, fly ash has two characteristics: a low content of CaO (3.02%) and ($SiO_2 + Al_2O_3 + Fe_2O_3 \geq 70\%$) – class F [12].

The rate of hydration process is getting slower with the replacement of cement with fly ash, and it also affects the decrease in compressive strength at an early age, which is the main property of concrete [10, 11, 13]. Meanwhile, by increasing fly ash, the heat of hydration will decrease, and microcracks on the concrete surface will disappear. This process leads to decreased shrinkage and helps to produce more compacted concrete [14, 15].

In this study, the objective is to investigate the correlation between low-lime fly ash in ordinary C-25/30 and high-performance C-50/60 concrete in the short and long term of examination, finding out the optimum utilization of fly ash in both cases, drying shrinkage, and setting time. If blended cement-fly ash in different percentages can promote some reasonable results, it can be used as a pozzolanic material for concrete production in particular destinations, reducing cement usage and the cost of concrete while also helping the environment.

To achieve these targets, research went through these steps: assessment of the environmental impact of waste material fly ash and cement production; analyzing all properties of low CaO content class F fly ash and its effect in concrete; and experimentally analyzing properties of concrete containing different percentages of fly ash to define the optimum amount.

2. Materials and Experimental Program

2.1. Materials

The cement used was normal Portland cement (PC, 42.5 N/mm²), and its chemical composition is given in Table 1. The specific gravity of the cement was 3.15. The initial and final setting times of the cement were 3.3h and 5.8h, respectively. The Blaine-specific surface area was 3360 cm²/g. Fly ash was obtained from Hitachinaka Thermal Power Station, in Japan. It belongs to class F because it is made from bituminous coal and contains a low amount of lime. The chemical composition and physical properties are listed in Tables 1 and 2. The specific gravity was 2.10 and the specific surface area was 2950 cm²/g.

Table 1. Chemical composition of cement and fly ash

Components	Cement	Fly ash
SiO_2 %	21.55	69.35
Al_2O_3 %	5.23	16.37
Fe_2O_3 %	2.88	3.72
CaO %	64.82	3.02
MgO %	1.19	0.57
SO_3 %	2.07	0.29
Na_2O %	0.64	1.50
K_2O %	-	1.05
MnO %	-	0.045
LOI %	0.53	4.27
Chromium VI mg/l	-	0.037
Moisture 105 ˚C %	-	0.06
CO2 %	-	0.71
Insoluble residue in HCL/Na_2CO_3 %	-	88.85
Insoluble residue HCl/KOH %	-	30.43
Reactive CaO %	-	1.91
Reactive SiO_2 %	-	43.23

Table 2. Physical properties of fly ash

Fineness %	FA
0.200 mm	0.0
0.090 mm	4.0
0.063 mm	8.0
0.043 mm	16.0
Capacity mass g/cm³	2.10
Specific surface cm²/g	2950
Flexural	2.9±0.4
Compressive	6.5±0.2

Aggregate: For this experiment, crushed-clean aggregate was divided into two fractions: fraction I (0–5) mm, or sand, and fraction II (5–15) mm, or gravel. The composition of these two fractions in concrete was 45% and 55%, respectively. The absorption value for sand was 1.3%, while that for gravel was 0.6%.

Additive: During casting high-performance concrete, respectively C 50/60, an additive with polycarboxylate polymer technology base from Sika (Japan) Sika Viscocrete Techno 20 was used, like powerful superplasticization for high-strength concrete. It is suitable for the production of high-demand concrete mixtures, offering water reduction and high flow ability at the same time.

2.2. Experimental Program

The research program on compressive strength was developed in two cases (cases A and B) and in a total of 12 different mix designs (see Table 3). Case A is ordinary concrete (C-25/30), and Case B is high-performance concrete (C-50/60). Based on the designed concrete recipe, etalon contains cement at 340 kg/m^3 for ordinary concrete and 440 kg/m^3 for high-performance concrete. This amount of cement was reduced in all mix designs by replacing it with fly ash (10, 15, 20, 25, and 30%). The next step in this experiment was to determine the water content. For control concrete, the water-to-cement ratio was 0.62% for A and 0.41% for B. It continued around this value for all other mix designs, considering w/(cement + fly ash). All the parameters mentioned above conform to curve S3 based on EN 12350-2; slump is determined to be between 100–150 mm. The results of the slump test investigation are shown in Table 3, including the concrete mixture composition for 12 different mix designs. For conducting case A, six different mix designs (M1–M6) were prepared and underwent testing procedures, and the same happened in case B with six other mix designs (M7–M12), including control concrete. In both cases, the objective was to find out the correlation between the different percentage contents of fly ash in two different types of concrete.

Table 3. Mixture proportion for 1m³ of ordinary (M1-M6) and high performance concrete (M7-M12)

Materials	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10	M11	M12
Cement (kg)	340	306	298	272	255	238	440	396	374	352	330	308
Fly ash (kg)	0	34	51	68	85	102	0	44	66	88	110	132
Sand (kg)	791	787	784	782	780	777	790	783	780	777	774	771
Gravel (kg)	968	961	958	956	953	950	965	958	954	951	946	943
Water (kg)	211	211.2	211.3	211.4	211.5	211.6	176	176	176	176	176	176
Additive (kg)	0	0	0	0	0	0	4.4	4.4	4.4	4.4	4.4	4.4
W/C ratio	0.62	0.62	0.62	0.62	0.62	0.62	0.34	0.41	0.41	0.41	0.41	0.41
Slump (mm)	120	125	128	132	137	142	111.5	120	125	130	138	150

The concrete mixtures were prepared in a laboratory mixer in typical mixing procedures: first coarse aggregate and sand together, followed by cement and fly ash; initially, dry material was mixed for 1 minute; finally, water was added; and the mixing continued for 2 minutes more. Altogether, more than 250 cylinder specimens were prepared, each 20 cm high and 10 cm in diameter. The filling was done in two layers, and then specimens were compacted on a vibration table until bubbles on the surface disappeared. The specimens were removed from molds after 24 hours and cured in water at a constant temperature until testing (after 3, 7, 21, 28, 56, ..., 625 days). All the compressive strength results were taken as the average of three readings.

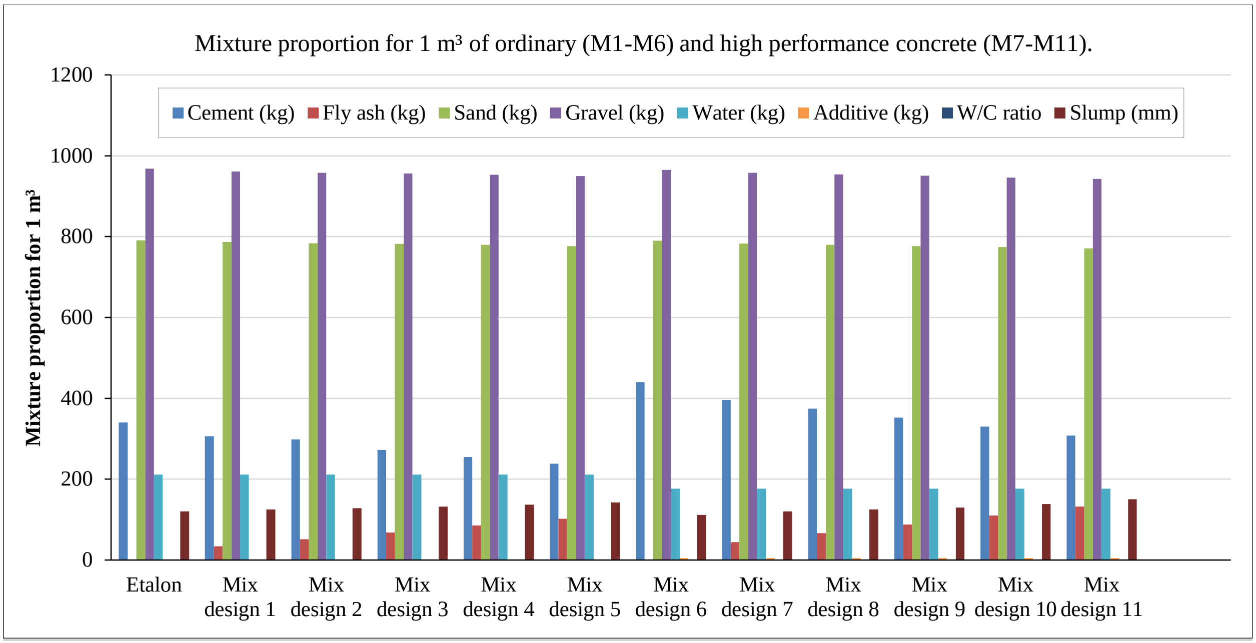

Figure 1. Components of 1 m³ of concrete for 12 different mix designs

Different cylinder specimens were prepared for shrinkage examination (see Figures 2 to 4). A very sensitive method was applied for the drying shrinkage investigation of six mix designs containing different percentages of fly ash (0, 10, 15, 20, 25, and 30%). For preparing these very delicate specimens (in terms of dimensions and preparation method), first sand was filtered, and only particles of 150 µ and under were used. The next step was the determination of the material ratio of cement, sand, and water, which was 1:2:2.1 (the amount of water was increased regarding the procedures of the specimens' preparation). After the specimens were put on molds, they were ven-dried for 24 hours at 40ºC. For moisture, they were clad with wet cotton rags and covered by a plastic bag. After being removed from molds, specimens were cured in water at a constant temperature of 22±2 ºC because of the hydration process of cement and fly ash, and then 12 empty cylinders went under examination. Six of them were put on the ports of the shrinkage instrument, and the other six were examined for weight loss. All of these were set in a chamber with a constant temperature of 22±2 ºC and 60±5% relative humidity for a period of time until the results were repeated continually and the examination was considered complete.

Setting time was conducted with a Vicat needle and according to ASTM C 191-08 [16]. In total, 10 different mixes were investigated. The first was the control design with only cement, which was replaced with different percentages of fly ash (10, 15, 20, 25, 30, 35, 40, 45, and 50%). All this was developed in laboratory conditions with constant temperature and humidity. During examining the experiment program, all parameters, procedures, and materials conformed to EN and ASTM standards [17–19].

Figure 2. Shrinkage specimen: h=100 mm, D=10 mm and d=8 mm

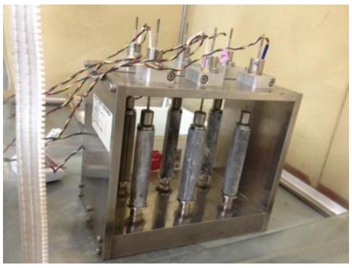

Figure 3. Specimens on the ports for measurement

Figure 4. Examination of shrinkage

3. Results and Discussion

3.1. Compressive Strength

The results of the compressive strength investigation for all mix designs are listed in Table 4. Results show that concrete at an early age will decrease compressive strength in both cases (A and B) by incorporating fly ash. By time, compressive strength increased, but until the end of the examination, control concrete showed better results compared with all other mix designs (fly ash + cement) concrete.

Table 4. Compressive strength of ordinary concrete C 25/30 and high performance concrete C 50/60

Mix	Compressive strength (MPa) C 25/30									
	3 Day	7 Day	21 Day	28 Day	56 Day	180 Day	270 Day	365 Day	460 Day	625 Day
M1	22.3	27.5	39.4	41.9	45.3	52.0	53.4	54.0	55.7	56.9
M2	14.7	18.0	22.2	25.2	38.1	43.3	43.8	44.5	47.0	50.1
M3	10.9	14.6	21.0	23.1	31.3	37.0	38.2	39.8	44.2	47.4
M4	8.7	13.2	18.9	22.4	30.4	37.0	38.0	38.9	41.9	43.8
M5	5.5	10.2	17.9	18.5	23.7	28.8	29.7	31.2	34.5	35.9
M6	4.1	5.9	15.8	18.1	18.5	18.9	19.8	21.2	25.9	26.1

Mix	Compressive strength (MPa) C 50/60						
	3 Day	7 Day	21 Day	28 Day	100 Day	180 Day	350 Day
M7	46.0	46.3	59.6	64.1	67.3	74.7	78.5
M8	36.8	43.5	56.7	62.4	65.0	70.6	74.1
M9	36.0	42.0	52.9	55.6	63.7	68.7	71.8
M10	37.7	44.4	55.5	56.9	60.0	65.0	68.9
M11	31.0	37.3	48.2	51.3	59.2	62.9	66.1
M12	25.2	32.5	35.1	37.6	53.6	57.0	60.0

Analyzing the results of case A for fly ash content at 30% after 3 days of examination, compressive strength was very low (4.1 MPa). By reducing fly ash content, compressive strength was increased to 14.7 MPa with 10% fly ash content at the same age. Meanwhile, as aging increased, the bonding of fly ash particles to the cement matrix increased, resulting in good results with 20% fly ash replacement in 180 days. The compressive strength was 37 MPa.

Almost the same impact fly ash has on case B, high-performance concrete. For 30% cement replacement with fly ash at 3 days of curing, compressive strength was 25.2 MPa, which was increased by decreasing fly ash content to 36.8 MPa for 10% fly ash content at the same age. At the age of 100 days, compressive strength was 60.0 MPa with 20% cement replacement by fly ash, while with 30% fly ash content, compressive strength was increased to 53.6 MPa for the same age of curing. The fact that in both cases A and B, to increase strength, some time is needed is explained by the very low pozzolanic activity of class F fly ash.

Mixing water, fly ash, and cement creates a pozzolanic reaction. In this situation, SiO_2 and Al_2O_3 react with $Ca(OH)_2$ and produce hydrates of calcium silicate, which decrease $Ca(OH)_2$ and increase C-S-H gel. This gel contributes to the structure of hardened cement [20]. So, the higher $Ca(OH)_2$ concentration in the chemical composition of fly ash leads to a longer pozzolanic process in both ordinary and high-performance concrete.

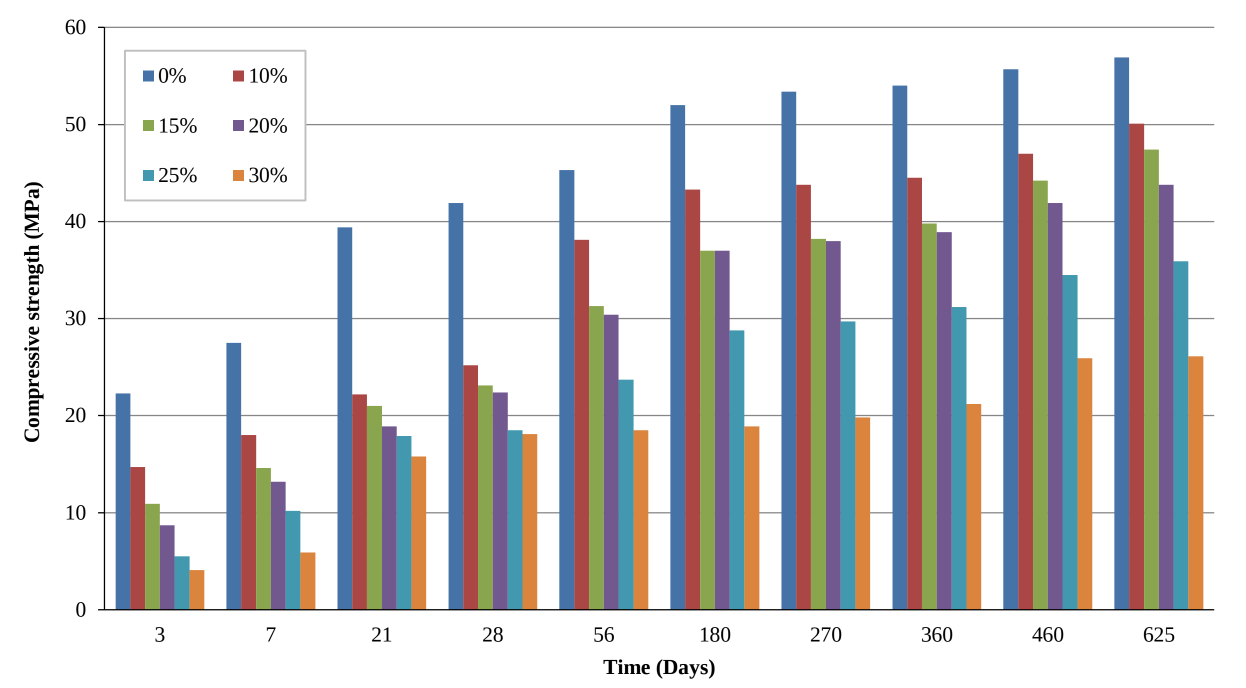

Figure 5. Relation between compressive strength and fly ash content – concrete C 25/30

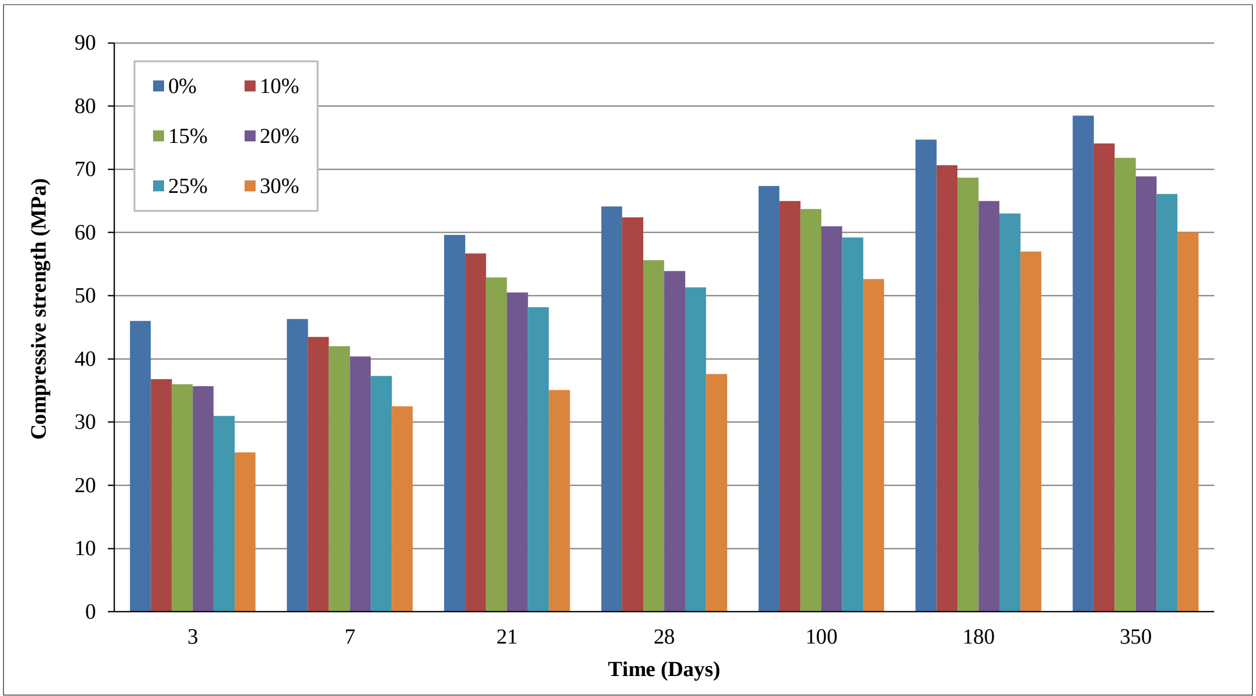

Figure 6. Relation between compressive strength and fly ash content - concrete C 50/60

3.2. Standard Consistency and Setting Time

To set the standard consistency of fly ash and cement paste in 10 different mix designs, it was noted that the requirement of water was increased slightly by increasing fly ash content [21]. The very fine particle size of fly ash implies a higher water content.

Figure 7 shows that the initial setting times and final setting times are prolonged as the replacement of cement by fly ash is increased. This happens because of the amount of water. During the examination, for all 10 different mixes, time was prolonged in a continuous way, but the phenomenon is that fly ash affects the final setting time more than the initial one. At 50% replacement of cement, the initial setting time is prolonged by 87 min, and the final setting time is prolonged by 168 min. Fly ash has a very low pozzolanic reaction rate, and its particle surface may be a conversion zone at the initial stages of hydration [22].

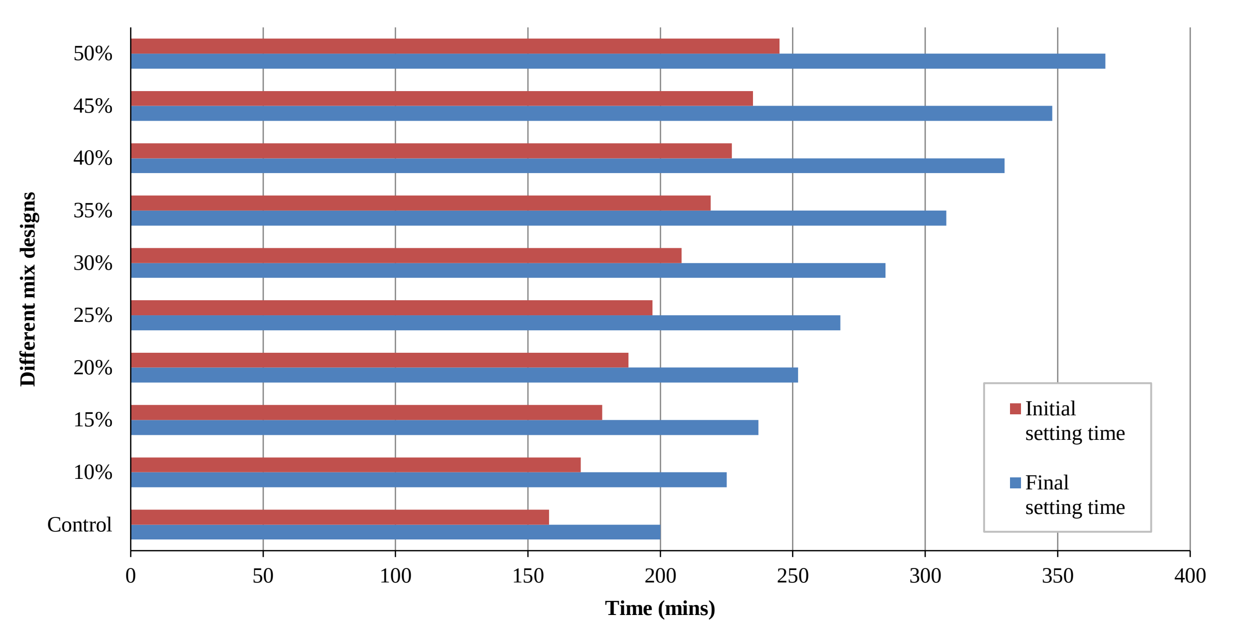

Figure 7. Setting time of fly ash – cement mortar

3.3. Drying Shrinkage

The drying shrinkage measurements started after the completion of 2 months of curing time. The shrinkage-empty cylinders were kept in a controlled chamber during examination. Initial readings were recorded at the time of placing empty cylinders in corresponding ports, and measurements continued to be recorded every 10 minutes until the examination was finished. The stability of length is related to water content. During all the time of the examination, relative humidity and temperature were kept constant, so the outside environment didn't affect the results. As a result of big pores (examination by microscope), the water was able to be removed quickly, in large amounts, without inducing high stress, and also shrinkage was smaller.

Figures 8 and 9 show the weight loss and shrinkage as ages increase. Figure 10 shows that fly ash mixes shrank less than control concrete at all ages, and the difference is considerable. Shrinkage increased as the amount of cement increased because of the hydration heat. The results on these charts show that fly ash can be considered a shrinkage-reducing agent. The chart clearly shows that the highest shrinkage was observed in control concrete compared to a mix with 10% fly ash, while increasing fly ash content by 15, 20, 25, and 30% showed a slight difference in results. This phenomenon is explained by the expansive properties of fly ash and the pozzolanic reaction. So, the incorporation of fly ash improves pore structure, or close micropores, because of the very fine particles of concrete and implicates a decrease in shrinkage [23, 24].

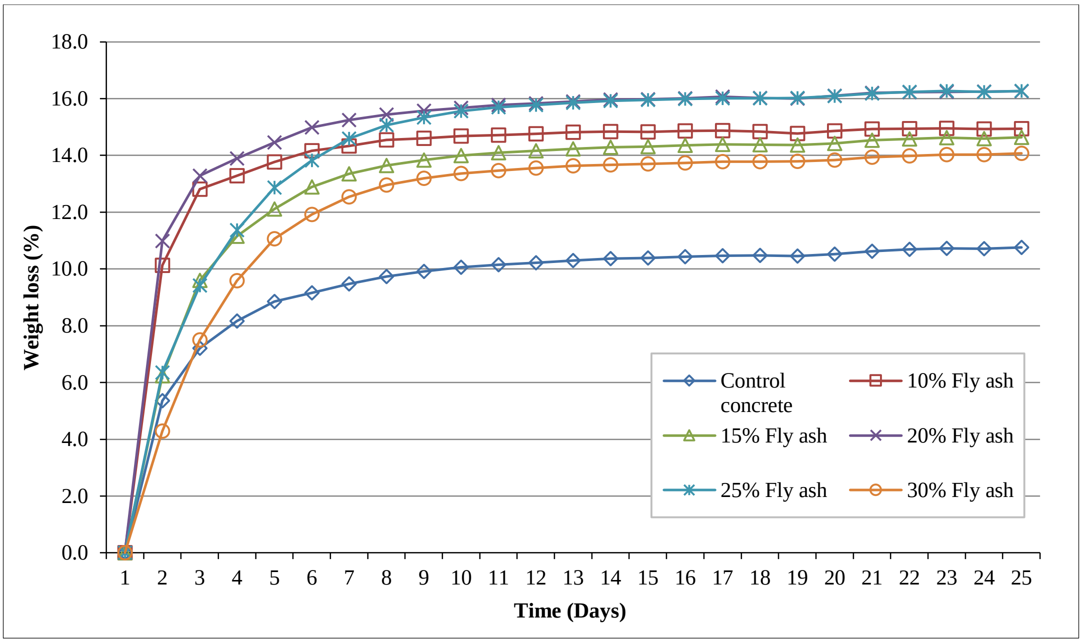

Figure 8. Weight change of mortar produced versus time

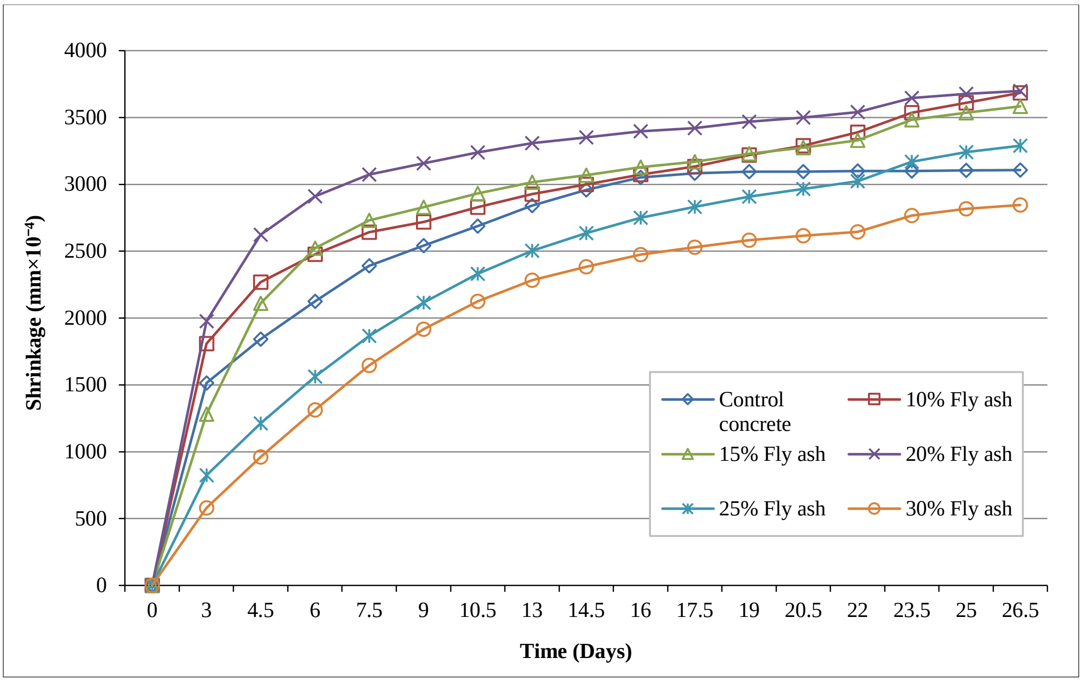

Figure 9. Length change of mortar produced versus time

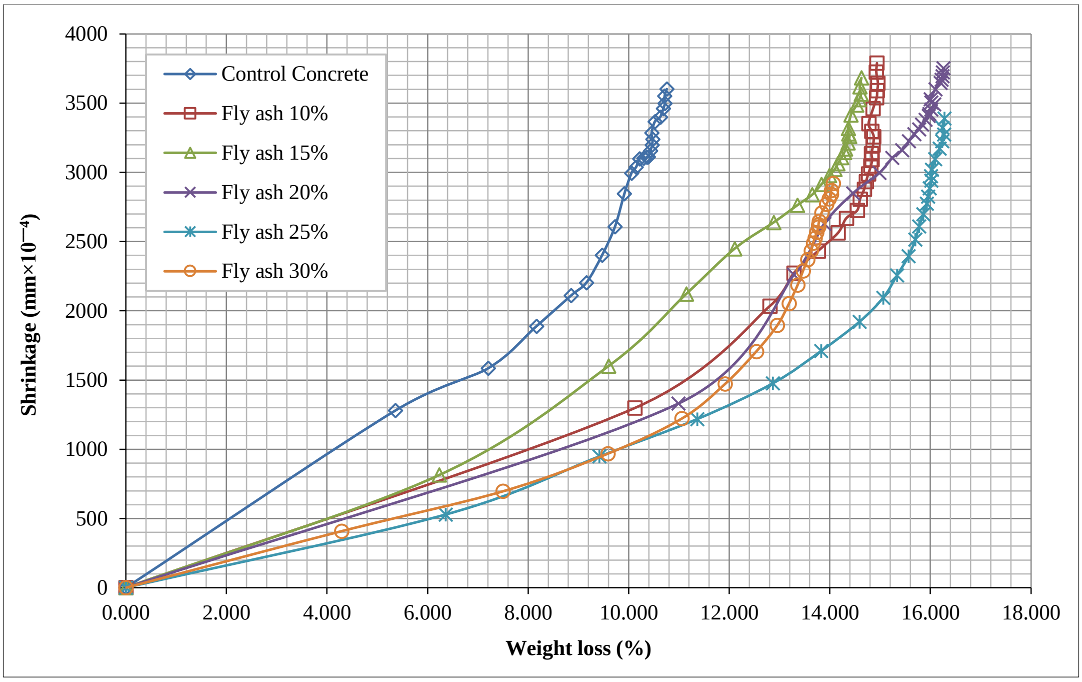

Figure 10. The relation between shrinkage and weight loss

4. Conclusion

Reducing environmental impact by using waste material and, at the same time, achieving good quality products at a lower price is very important for developing the construction industry in this century. Incorporating low CaO content class F fly ash in concrete will reduce the requirement for cement production by 30%. As a result, CO_2 emissions will reduce and global warming will also reduce. 1 ton of fly ash in concrete will avoid 1 ton of CO_2 emissions from cement production, decrease the price, and save the landfill.

Due to the spherical shape of fly ash grains, the workability of fresh concrete was increased by increasing fly ash content. The mass of fresh concrete was sticky without any segregation. During the examination for initial and final setting, time was prolonged, and as fly ash content increased, setting time was longer. This effect happens for two reasons: 1) increasing water requirement by increasing fly ash content; and 2) high concentration of $Ca(OH)_2$, which contributes to a very high and very long pozzolanic process. It is important to note that the final setting time was 52% longer than the initial one. Regarding compressive strength, low CaO content in Class F of fly ash had the same effect in both cases (cases A and B). Compressive strength is related to many effects: the chemical composition and physical properties of fly ash, the amount of ash content, and curing time. During the development of this study, all of these factors were considered, and it was possible to gain expected results like: mix design with 30% fly ash content was achieved for ordinary concrete C 25/30 and high-performance concrete C 50/60 for 180 days. While experimental examinations approved that fly ash can improve the pore structure of concrete, fly ash-concrete mixes were shrank less than control concrete at all ages. Shrinkage was reduced by increasing fly ash content; fly ash can be used as a shrinkage-reducing agent.

5. Declarations

5.1. Author Contributions

Conceptualization, A.A. and T.N.; methodology, A.A.; validation, T.N. and A.A.; investigation, A.A.; data curation, V.K.; writing—original draft preparation, A.A.; writing—review and editing, A.A., V.K., and T.N.; supervision, A.A.; funding acquisition, T.N. All authors have read and agreed to the published version of the manuscript.

5.2. Data Availability Statement

The data presented in this study are available on request from the corresponding author.

5.3. Funding

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5.4. Conflicts of Interest

The authors declare no conflict of interest.

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