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Effect of Non-Class Fly Ash on Strength Properties of Concrete

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Abstract

Developing of green construction and reducing CO_2 emissions in the environment is a priority for industry in the coming years. Recycling fly ash in the concrete industry is a well-known way to reduce environmental impact. Aside from this benefit, there are numerous other positive effects of incorporating fly ash into concrete; however, in this research, the objective is to replace cement with a different percentage of non-class fly ash with high CaO, more than 42%. The analyzed variables are non-class fly ash properties, the effect of fly ash presence on the main properties of concrete and examining the optimum of non-class fly ash in ordinary concrete C-25/30 and high-performance concrete C-50/60. All investigations took place in the laboratory by producing 24 different mix designs and more than 1000 specimens to examine: consistency, setting time, shrinkage, and compressive strength in the short and long terms of curing. Recycling industrial waste in new construction, especially fly ash because of its non-uniform properties, still has some obstacles and is not a practical issue, but the future must be environmentally friendly, and this research proves that the objective of producing sustainable ordinary and high-performance concrete was achieved by replacing 40% of cement with non-class high CaO content fly ash.

Keywords: Non-Class Fly Ash; Compressive Strength; Shrinkage; CO_2 Emission.

1. Introduction

A way to produce sustainable concrete is by reducing CO_2 emissions by decreasing cement production instead of incorporating industrial waste as fly ash [1, 2]. Cement as a bonding material, the basic material for concrete, causes 8% of total greenhouse gas production, which causes global warming and climate change [3, 4]. Meanwhile, fly ash does not have uniform properties and is still not specified as a quantified fly ash type for concrete mixtures. This research investigates non-class high CaO fly ash in the mass of concrete from Kosovo, its environmental impact, and its concrete properties. Furthermore, concrete is the most widely used construction material in the modern world because of its characteristics compared to other materials, which are: excellent strength, easy shape, long-lasting service, affordability, easy to obtain etc. [5, 6].

Hence, utilization of supplementary cementitious materials (SCM) such as industrial waste has been a global trend for decades. In Brazil, according to this strategy, CO_2 emissions are reduced by ~ 4.4% due to the clinker content of cement. Research institutions in Canada are pioneers in the research of using high volumes of SCM in the concrete industry [7]. India has stipulated by law the utilization of fly ash in construction materials, especially in concrete, road construction, and bricks. The Ministry of Environment and Forestry has announced the benefits of recycling this industrial waste and saving natural resources [8, 9]. Australia alone is producing more than 12 million tons of fly ash per year. 43% of this ash is re-used for various applications, including the construction industry, while the rest is being dumped as waste, causing environmental problems such as groundwater contamination, spills from bulk storage, and

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ground pollution by heavy metals [10–12]. Apart from environmental benefits, fly ash contributes to other properties such as workability, expansive property [13], permeability [13], and other durability attributes [14].

The benefits of utilizing fly ash for concrete applications are threefold: savings in CO_2 emissions, reducing the disposal of fly ash into the environment, and improving concrete qualities. So, these strategies have more advantages than reducing CO_2 emissions; they also conserve natural resources, reduce the disposal of fly ash into the environment, and increase production quality. Although there is numerous research about incorporating fly ash into concrete, there still remains an important scope to analyze the utilization of different types of fly ash in concrete. Usually, studies are focused on general issues and not studding environment effects and concrete quality based on fly ash types. The impact varies completely from type of fly ash used [23], and the concrete mixture has to be designed based on the type of fly ash. Low CaO fly ash is more effectively used for concrete resistance to alkali, silica, sulphate attacks, and acid resistant [13–15]. Concrete will be more durable to aggressive environment. High CaO fly ash is better to improve the early compressive strength of concrete because of its higher reactivity.

In order to reduce the environmental impact of CO_2 emissions, the government of Kosovo should promote and develop a sustainable construction industry with the aim of reducing cement production by up to 40% and replacing it with lignite coal fly ash obtained during the burning process of coal for the production of electricity in thermal power plants. Generally, fly ash is gained from the process of burning coal to produce electrical energy in power plants, which results in a high volume of CaO content and non-class fly ash. Its properties are different based on the type of coal and the technology used for burning it, but as long as fly ash fulfills the requirements of standards (EN, ASTM, JIS, etc. based on which country is applied), it can be used in the construction and concrete industries. Basically, according to ASTM, fly ash is divided into two categories: Class C ($SiO_2 + Al_2O_3 + Fe_2O_3 \geq 50\%$) and Class F ($SiO_2 + Al_2O_3 + Fe_2O_3 \geq 70\%$) [16–18].

To date, the majority of prior research on fly ash recycling has focused on using it in concrete for different purposes; none of the studies have optimized and found the effect of different types of fly ash in the concrete industry, especially when fly ash does not meet standard requirements, does not belong to any of the above-mentioned classes, and has a high CaO content. In the present research, three goals will be explained: The first goal is to determine the mechanical properties of ordinary and high-performance concrete for short- and long-term curing when the content (10, 15, 20, 25, 30, 35, 40, 45, and 50%) of cement replacement with non-class and high CaO content of fly ash; the second goal is to find the optimum amount of this type of fly ash to produce ordinary and high-performance concrete; and the third goal is to find a reduced amount of CO_2 emissions after including this type of fly ash in concrete production in Kosovo and other environmental effects.

2. Materials and Experimental Program

2.1. Materials

The cement used was a market-available PC 20M (S-L) 42.5R, equivalent to EU standards, while fly ash was discharged from power plant Kosova B directly after the process of burning coal to produce electrical energy. The physical properties and chemical compositions of cement and fly ash are given in Tables 1 and 2.

Table 1. Chemical composition of non – class fly ash

Fineness	Non-class Fly ash
* 0.200 mm	0.1
* 0.090 mm	4.9
* 0.063 mm	8.1
* 0.043 mm	12.5
Capacity mass g/cm³	2.83
Specific surface cm²/g	6600
Flexural MPa	4.5 ± 0.3
Compressive MPa	21.1 ± 0.7

Table 2. Physical properties of non-fly ash

Materials	Compound											
	Al_2O_3	SiO_2	SO_3	K_2O	CaO	MnO	Fe_2O_3	MgO	Na_2O	LOI	Moisture 105 C°	Reactive CaO	Reactive SiO_2
Non-class Fly ash %	5.67	19.28	19.41	0.36	42.92	0.08	4.85	4.31	0.58	2.3	0.29	28.44	15.69
Cement %	6.13	19.79	2.98	0.68	63.86	-	2.73	2.42	0.19	4.14	-	-	-

To obtain high-performance concrete C 50/60, an additive based on polikarboksilat polymer was used. It contributes to meeting high demands and increasing the flow properties of fresh concrete; a constant amount of 1% cement was used in all mix designs. Conducting this experiment was used crushed-clean aggregate, which was divided into three fractions: I - (0-4) mm, II - (4-8) mm, and III - (8-16) mm. The composition of these three fractions in concrete is 45%, 22%, and 33%. The absorption value of sand was 1.1%, while for aggregate was 0.7%.

According to chemical compositions $SiO_2 + Al_2O_3 + Fe_2O_3 = 19.28 + 5.67 + 4.85 = 29.8\%$, Kosovo fly ash, which becomes from lignite coal, does not belong in class F or C based on ASTM standards. What is very important to analyze are the large specific surface of fly ash (6600 cm^2/g), spherical-shaped particles compared to angular-shaped cement particles, and the high content of CaO (42.92%). Kosovo fly ash has 19.42% of SO_3 and failed to satisfy restrictions of ASTM, BSI, and EN for SO_3 content in fly ash in order to use it in concrete. Based on standards, it should be 5%, 2.5%, and 3.0%.

2.2. Mix Designs and Details

The experimental research is divided into three parts; consequently, three mixtures were without fly ash, control concrete, while twenty-one other mixtures were designed with different percentages of fly ash content, starting from (10, 15, 20, 25, 30, 35, 40, 45, and 50%) replacing cement. In total, twenty-four mixtures with a water/binder ratio between 0.4–0.6 were cast. The material proportions remained constant, and the slump test for all mix designs conformed to curve S3, ranging between 100-150 mm. Mixture details are listed in Table 3 and Figure 1.

Table 3. Mixture proportions for 24 mix designs

Case	Mixtures	Cement (kg)	Fly ash (kg)	Sand (kg)	Gravel (kg)	Water (kg)	Additive (kg)	w/b ratio	Slump test (mm)
Case 1	M 1	290	0	868	1061	160.7	1.74	0.61	140
	M 2	261	29	864	1056	160.7	1.74	0.62	130
	M 3	246.5	43.5	862	1054	160.7	1.74	0.62	122
	M 4	232	58	860	1052	160.7	1.74	0.63	130
	M 5	217.5	72.5	827	1010	160.7	1.74	0.63	130
	M 6	203	87	856	1046	160.7	1.74	0.63	140
	M 7	174	116	860	1050	160.7	1.74	0.63	130
	M 8	145	145	859	1049	160.7	1.74	0.63	140
Case 2	M 9	340	0	791	968	211	0	0.62	122
	M 10	306	34	787	961	211.2	0	0.62	123
	M 11	298	51	784	958	211.3	0	0.62	125
	M 12	272	68	782	956	211.4	0	0.62	126
	M 13	255	85	780	953	211.5	0	0.62	130
	M 14	238	102	777	950	211.6	0	0.62	133
	M 15	204	136	781	949	211.3	0	0.62	135
	M 16	170	170	779	951	211.1	0	0.62	139
Case 3	M 17	440	0	790	965	176	4.4	0.34	137
	M 18	396	44	783	958	176	4.4	0.41	132
	M 19	374	66	780	954	176	4.4	0.41	138
	M 20	352	88	777	951	176	4.4	0.41	145
	M 21	330	110	774	946	176	4.4	0.41	141
	M 22	308	132	771	943	176	4.4	0.41	143
	M 23	264	176	775	945	176	4.4	0.41	148
	M 24	220	220	781	949	176	4.4	0.41	146

An additive based on polikarboksilat polymer was added to eight mix designs to achieve high-performance concrete C 50/60. The amount of additive was kept constant in all eight mixtures: 1% of cement + fly ash.

The fresh properties of concrete mixtures were determined through consistency and density tests. Slump values are measured in conformity standard EN 12350-2 (see Table 3). The fresh densities were determined by the quotient of their mass and the volume, with values between (2.39 – 2.45) g/cm^3 for the first part of the research, (2.22 – 2.34) gr/cm^3 for the second part, and (2.38 – 2.39) gr/cm^3 third part. The fresh densities of mixtures are also shown in Table 3. The very fine rosary shape of fly ash particles contributes to the increase in workability of fresh concrete by reducing segregation and helping to gain very sticky mass. Increasing fly ash content contributes to improving the properties of fresh concrete. Concrete specimens are molded and cured under standard conditions until testing age.

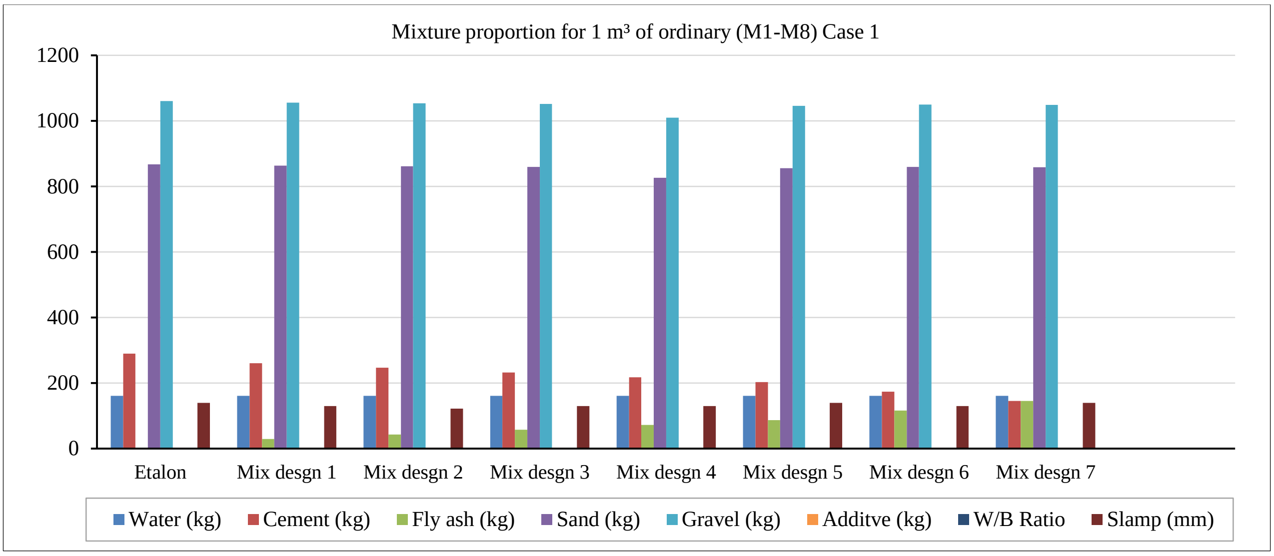

Figure 1. Components of 1 m³ of concrete for 8 different mix designs

2.3. Test Procedures

The concrete mixture was prepared in a laboratory mixer. During typical procedures, mold filling was done in two layers using a vibration table until the bubbles on the top of fresh concrete specimens disappeared. Specimens were removed from molds after 24 hours and cured in water at a constant temperature until testing after 3, 7, 21, 28, 56, 100, 180, and 365 days, then after 3, 5, 7, and 10 years. Altogether, more than 1000 specimens, 15 cm cubes, and all compressive strength results were taken as the average of three readings. For the casting shrinkage experiment, a very sensitive method was used, with 1 mm-thick empty cylinders measuring 1 cm in diameter and 10 cm in height. For this examination, in total, six mix designs were prepared according to the mix design of the first part of this research, with a difference in fly ash content of 0, 10, 15, 20, 25, and 30% of cement substitution. For preparing these very delicate specimens (in terms of dimensions and preparation method), sand was filtered and particles until 150µ were used. The material ratio was determined to be cement: sand: water = 1:2:2.1. After the samples were put on molds, they went under the oven to dry for 24 hours at 40°C. To keep specimens in a moist environment, they were clad with wet cotton rags, and to prevent humidity evaporation, specimens were put in closed plastic bags. After specimens were removed from molds for three months, they were cured in water at a constant temperature of 22±2 °C to complete the hydration process of cement + fly ash, and then 12 empty cylinders went under examination. Six of them were put on very sensitive measuring ports of the shrinkage instrument (measures were done every 10 min) and the other six were examined for weight loss. All 12 specimens during the examination were set in a chamber with a constant temperature of 22±2 °C and a relative humidity of 60±5% until the end of the examination (Figure 2).

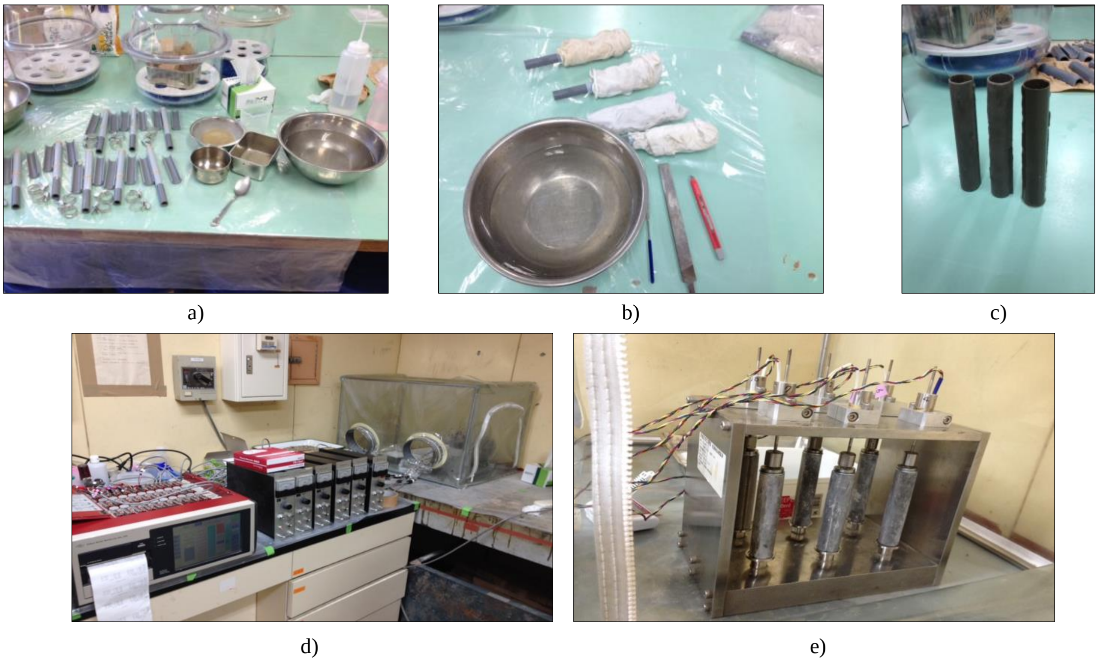

Figure 2. Process of shrinkage specimen's preparation and examination: a) molds and concrete, b) specimens after 24 h, c) shrinkage empty cylinders h=10cm, D=1cm and d=1mm, d) examination process and e) empty cylinders on corresponding ports in chamber

Setting time was also in focus during the examination, which was conducted by a Vicat needle according to ASTM 191-08. Firstly, the standard consistency was determined for 10 different mix designs with 0, 10, 15, 20, 25, 30, 35, 40, 45, and 50% cement replacement with fly ash. During casting and examination, all procedures were developed according to standards and in laboratory conditions.

a)

b)

Figure 3. Examination of setting time of concrete: a) preparation of mass with standard consistency, b) examination with Vicat needle

3. Results and Discussion

3.1. Compressive Strength

The compressive strength evolution shows that the strength gain over time depends on the cement ratio replaced by fly ash. At 7 days by w/b ratio between 0.4 and 0.6, in three different cases, the gain of strength in etalon was relatively high, more than 70% for the first and second cases, and more than 85% in the third case of research on its 28-day compressive strength. In all three treated cases, when part of the cement was replaced by fly ash, the compressive strength decreased compared to reference concrete. By increasing the curing time of the specimens, compressive strength was also increased (see Figures 4 to 6). For instance, the first case, after 180 days of curing specimens with 30% fly ash content, achieved class C 25/30, and it continued to increase in strength over time. After 365 days, the mix design with 40% fly ash content gained a quality of C 25/30. Almost the same thing happened in the second case: after one year of curing, the mix design with 40% fly ash achieved quality C 25/30. Based on these dates, the different content of cement does not play any role in curing specimens for a long time. According to the third case, dates show better results; in 100 days, class C 50/60 of concrete was obtained, a mixture with 40% cement replaced with fly ash.

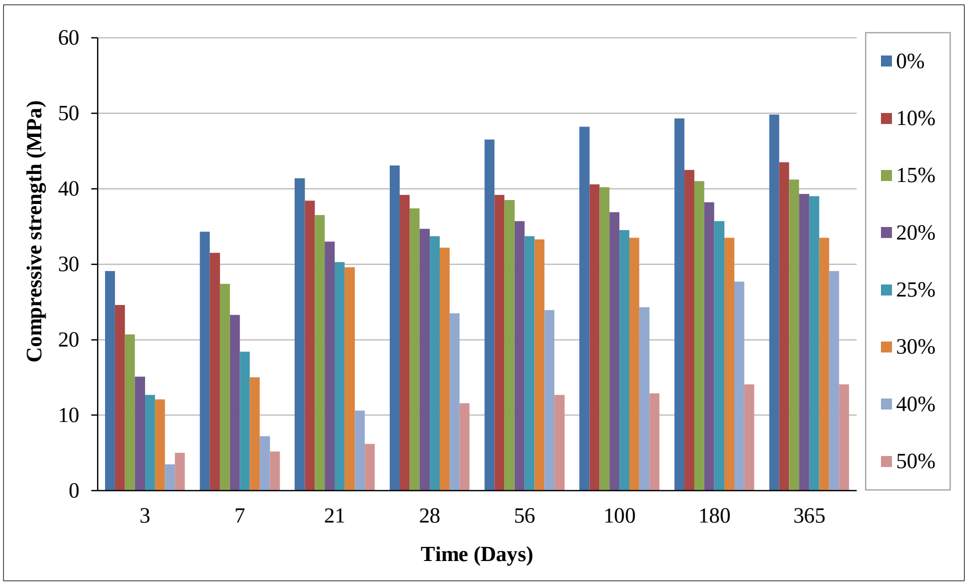

Figure 4. Relation between compressive strength and fly ash content - concrete C 25/30 - Kosovo case. With only 290 kg/m^3 of cement content on etalon and adding additive

Analyzing Compressive strength progress vs. curing time is mainly dependent on the hydration rate of cement for etalon, while in the other 21 mixtures, it depends on the combination of hydration of cement + pozzolanic reaction of fly ash, which during this examination, differently from other fly ash types, started in the early ages. So, the progress of strength development in three cases has been continuous and constant since the beginning, while the intensity of strength increase has decreased continually over time. Indeed, at mixtures with a high content of fly ash (40 and 50%), strength improvement was delayed, but based on the results, the requested quality of concrete was achieved and exceeded in time. While mix design with 30% low CaO fly ash content was achieved for ordinary concrete C 25/30 and high-performance concrete C 50/60 for 180 days, the intensity of strength increase was too low for considering improving strength during a long time of curing [19].

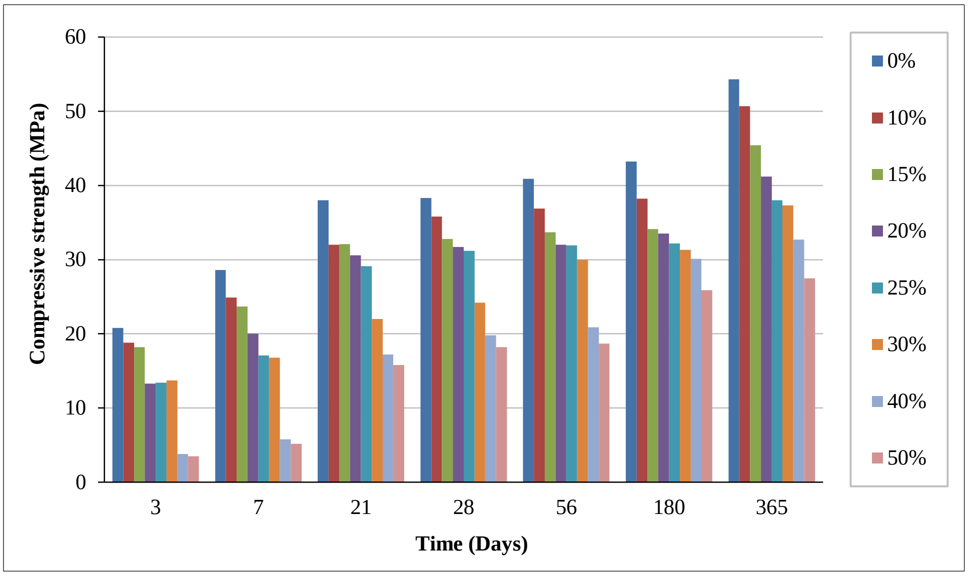

Figure 5. Relation between compressive strength and fly ash content - concrete C 25/30 - Kosovo case

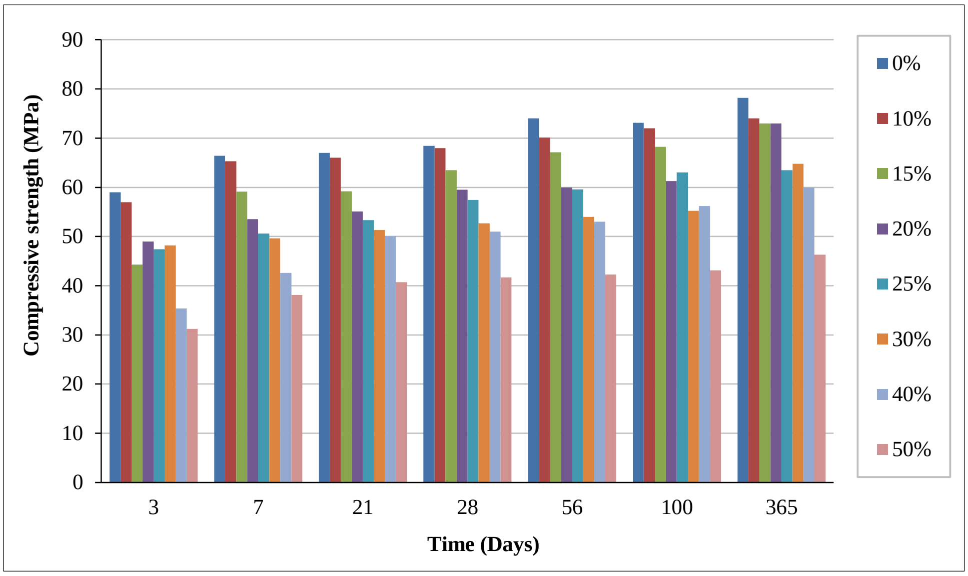

Figure 6. Relation between compressive strength and fly ash content - concrete C 50/60 - Kosovo case

3.2. Standard Consistency and Setting Time

To examine standard consistency, we designed 10 different mixtures of cement and fly ash pastes, starting with (0, 10, 15, 20, 25, 30, 35, 40, 45, and 50%) of the high CaO content of fly ash. Related to the very fine particles of non-class fly ash content, the water requirement was increased. Consequently, increasing fly ash content will also increase water content.

Figure 8 shows that the initial setting time and final setting time are prolonged due to increased water. Differently from expectations and other research, using high CaO fly ash contributes to prolonging the initial setting time more than the final setting time. For instance, in a mixture with 50% fly ash content, the initial setting time was prolonged for 94 minutes, while the final setting time was prolonged for 105 minutes. This is regarding the very high content of CaO as a reactive part of the non-class fly ash content. The very large specific surface of this non-class fly ash helps to develop the hydration process since it is in its early stages. Compared to setting time with low CaO content, where the final setting time was 87 minutes due to the little water requirement and the final setting time was 168 minutes because of the little content of the reactivity substance [19].

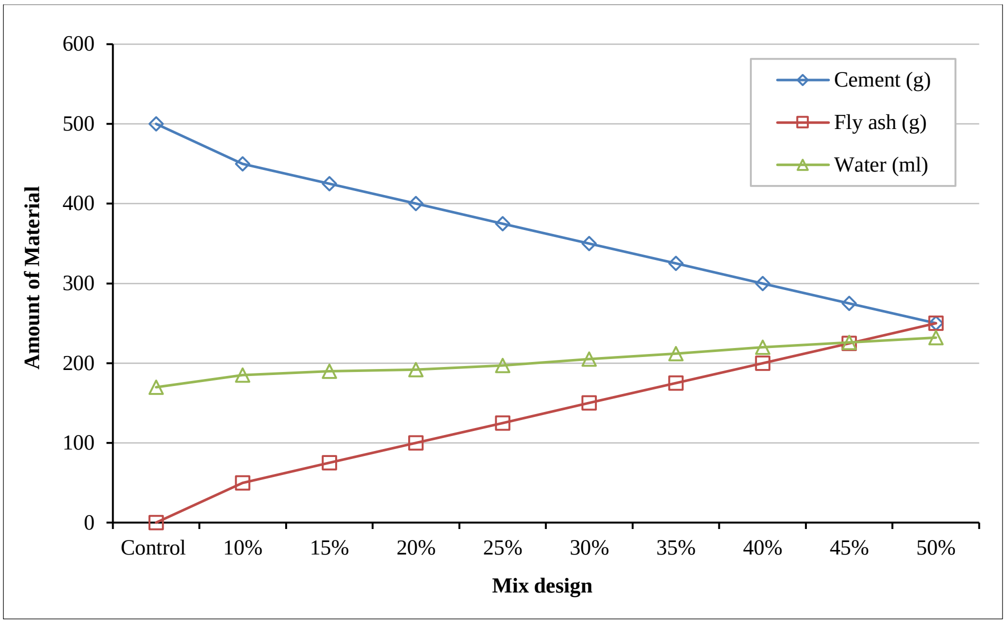

Figure 7. Material used in different mix designs during testing

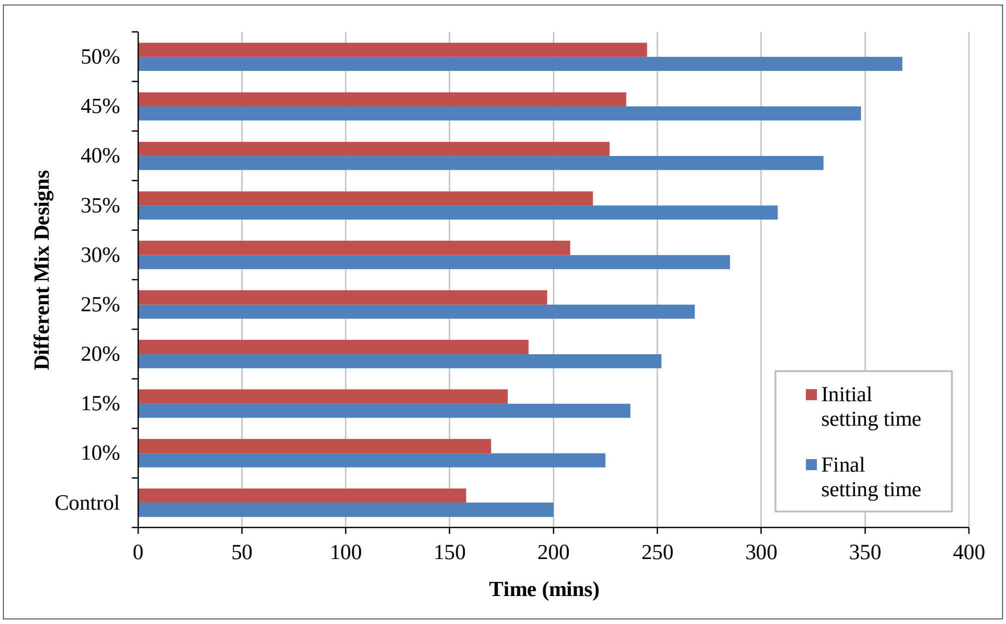

Figure 8. Setting time of fly ash-cement mortar

3.3. Shrinkage

To measure shrinkage, a very sensitive method was established called QUICK for concrete shrinkage examination. Figures 5 and 6 show that weight loss and shrinkage increase as ages increase for control concrete. Fly ash content helps to improve the pore structure of concrete, and this causes fly ash mixtures to shrink less at all ages, and the difference is considerable. Fly ash contributes to closing big pores, so the water is removed very slowly from small pores. During this process, according to capillary stress theory, an increasing internal hydrostatic stress was developed as the capillary pores became smaller. For instance, in a mixture with 10% weight loss, shrinkage was 1700mm $\times 10^{-4}$ mixture with 20% fly ash content. And in mix designs with low CaO fly ash content, big pores were not closed, and as a result, water evaporated soon and the stress on capillary pores was very low. So, the examination was short, and the shrinkage was 1150mm x 10^{-4} for the mix design with 20% fly ash; the difference is 550 mm $\times 10^{-4}$ [19].

A higher amount of cement content increases the heat of hydration and consequently causes shrinkage. As the amount of fly ash content increases, the shrinkage decreases, and concrete will become compact as a result of improving pore structure by expansive properties of fly ash and the pozzolanic reaction [20, 21].

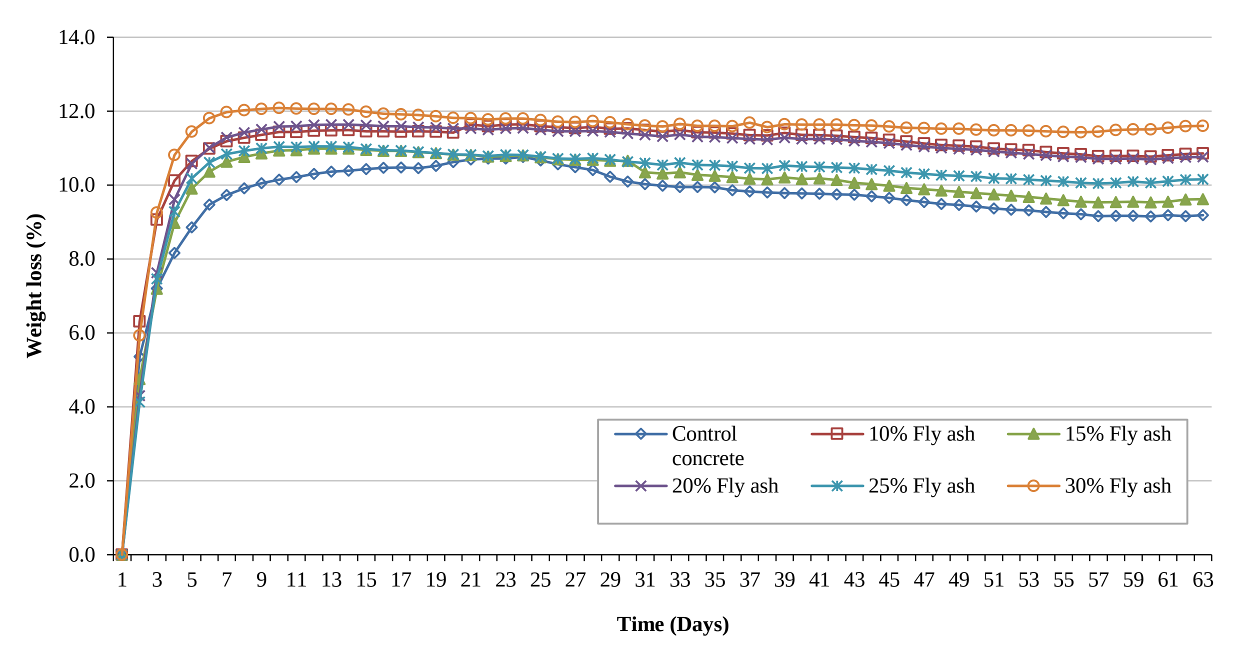

Figure 9. Weight loss of concrete specimens versus time

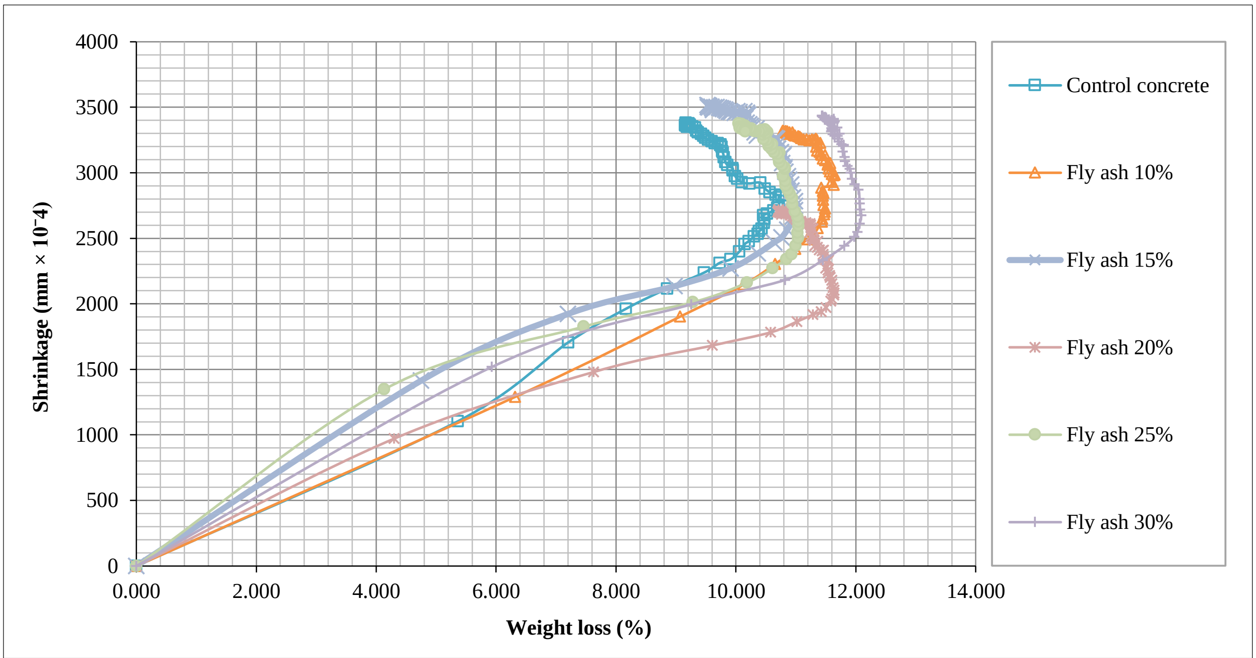

Figure 10. Shrinkage of concrete specimens versus weight loss

4. Conclusion

Developing a sustainable construction industry is very important based on the EPA's agenda to reduce environmental effects and CO_2 emissions. Concrete is the most widely used construction material, and it is still irreplaceable. Using fly ash to decrease cement production until 35–40% means reducing CO_2 release from 8% to 5.2–4.8%, reducing the price of concrete by 40% of its value, and improving the mechanical properties of the product. It is also important to consider the transport distance from the power plant to the construction site. In this case, Kosovo is a small country, and at the same time, 93% of electricity is produced from burning lignite coal in Obiliq, so the amount of fly ash is going to increase in the coming years. Increasing fly ash content implicates increasing water content. It happens with very fine particles of fly ash; that's why the strength progress of concrete takes more time than control concrete, but it is compensated by the high reactivity of the CaO content. The same effect was observed at compressive strength and shrinkage examinations. Due to the very fine particles of fly ash, the rosary shape helps to increase workability by increasing fly ash content, and the mass was sticky without segregation. The high content of CaO in fly ash is a very important component for using it to produce concrete. This contributes to speeding up the hardening process and the properties of the final product.

During the examination of the initial and final setting times, it was observed that the final setting time was prolonged only 10.5% longer than the initial one for a mixture with 50% fly ash content. This effect happened for two reasons: 1) the initial setting time was prolonged regarding the amount of water required to design standard consistency; and 2) the final setting time was fast regarding high pozzolanic activity and the hydration process as a result of the high amount of CaO content. Regarding compressive strength, high CaO content in non-class fly ash has the same effect in three investigated cases. Compressive strength is related to many factors, but according to this examination, incorporating fly ash with very high pozzolanic activity will increase continuously with time. The intensity of the strength increase will decrease with time, but it will not stop, and very good results can be achieved in the long term even with a high content of this industrial waste, up to 40%. The high specific surface area of non-class fly ash particles contributes to improving the pore structure of concrete, and to reduce concrete shrinkage, it can be used as a reducing shrinkage agent. Because of the expansive property, it helps to close the large porosity of the concrete mass, so the water is removed very slowly from small pores, and the amount is very small by inducing high stress. The examination lasted for 61 days, two times longer than in the case of fly ash with low CaO content.

5. Declarations

5.1. Author Contributions

Conceptualization, A.A. and T.N.; methodology, A.A.; validation, T.N. and A.A.; formal; investigation, A.A.; data curation, N.K.; writing—original draft preparation, A.A.; writing—review and editing, N.K.; supervision, A.A.; funding acquisition, N.K. 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 in the article.

5.3. Funding

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5.4. Conflicts of Interest

The authors declare no conflict of interest.

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