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Eco-friendly Hybrid Concrete Using Pozzolanic Binder and Glass Fibers

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ABSTRACT

Hybrid Concrete focused on development of buildings, highways, and other structures of civil engineering. In the current study, various mix combinations have been prepared and tested with different percentages of super-plasticizer at different levels of water reduction for obtaining the optimum mix. Further, study on different properties of hybrid concrete and replacement of ordinary portland cement (OPC) with ground granulated blast furnace slag (GGBFS), silica fume (SF) and glass fibers (GF) for obtaining highly cement replaced concrete (HCRC) and glass fiber concrete (GFC). The concrete performance was evaluated based on slump cone test, compressive strength test, split tensile strength test, flexural strength test, water absorption test and ultrasonic pulse velocity test. It was observed from the results that, the best performance of HCRC achieved at 50% GGBFS and 3% silica fume replacement. Further, in the case of GFC, 0.2% of glass fibers showed high performance in terms of split tensile and flexural strength at all ages. The optimized concrete mixtures like HCRC and GFC performed better than the control concrete (CC).

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1. INTRODUCTION

In today's world, the usage of concrete was increased enormously in different construction activities. One of the most important ingredients in the production of concrete was ordinary Portland cement. The high production of concrete involves more manufacturing and utilization of cement. The manufacturing process of cement leads to a huge release of CO_2 which results in environmental problems [1]. Because of this, many investigations have been carried out to find substitutes for cement which are cost-effective and environment-friendly. From the available literature, the substitutes to cement with different industrial by-products like fly ash, GGBFS, silica fume, metakaolin, rice husk ash, etc., had shown improved concrete properties [2–12]. Among various substitutes, GGBFS by-product gives good binding which results in improved artificial aggregates and concrete properties [13–15].

The utilization of various industrial by-products in concrete became popular because of their pozzolanic nature which improves the effective packing of mortar matrix with aggregate results in a solid concrete mix with very fine pore structure [16–18]. For the production of hybrid concrete, one part where the focus required was the mix design of concrete where the correct dosage of super-plasticizer was fixed based on water reduction percentage to improve concrete properties with the maximum replacement of cement content. Moreover, in this study, so many trials were conducted and tested to fix the exact dosage of super-plasticizer with an optimum percentage of GGBFS, SF, and GF. Through this study, the inclusion of GGBFS, SF, and GF to produce HCRC and GFC has been reported.

2. RESEARCH SIGNIFICANCE

The Portland cement which was an important ingredient of ordinary concrete plays the main role in obtaining the strength properties of concrete. But nowadays cement manufacturing leads to a huge release of CO_2 which results in environmental problems. Due to this, the investigation on different properties was carried out to

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substitute maximum cement content with GGBFS, SF with addition of GF to make concrete more effective and economical.

3. EXPERIMENTAL PROGRAM

3. 1. Materials

For the manufacturing of concrete specimens, different materials were used as follows and the physical and chemical characteristics of them are summarized in Table 1.

3. 1. 1. Cement

Ordinary Portland cement (OPC) of 53 grade was utilized in the entire study which was conforming to the BIS: 12269-2013 [19].

3. 1. 2. Industrial By-products

Industrial by-products like GGBFS and SF were used as partial replacement of OPC in this study. Both GGBFS and SF materials have been supplied by Aastra chemicals Chennai, which satisfies the requirements recommended by ASTM C1240-14 and ASTM C1240-15.

TABLE 1. Chemical and physical characteristics of different materials used in this study

Observations	OPC	GGBFS	SF
Chemical Characteristics			
SiO_2	22.3	35	99.88
Fe_2O_3	3	0.95	0.040
Al_2O_3	6.93	17.7	0.043
CaO	63.5	41	0.001
MgO	2.54	11.3	-
TiO_2	-	-	0.001
Na_2O	-	0.2	0.003
K_2O	-	-	0.001
$Ca(OH)_2$	-	-	-
MnO_2	-	2.7	-
SO_3	1.72	-	-
$CaCO_3$	-	10	-
P_2O_5	-	0.65	-
Glass content	-	92	-
Physical Characteristics			
Specific gravity	3.12	2.85	2.63
Appearance (powder)	Grey	Off-white	White
Specific surface area (m^2/kg)	290	409	819
Loss on ignition	0.84	0.26	0.015
pH Value	6.3	-	6.90
Moisture (%)	-	0.10	0.058

3. 1. 3. Aggregates

Crushed stone confirming to graded ordinary aggregates of size not more than 20mm as coarse aggregate and locally available natural river sand was used as fine aggregate which confirming to grading Zone II of BIS: 383-1989 [20]. The sieve analysis of natural aggregate and sand are given in Table 2.

3. 1. 4. Water

Potable tap water was used for the preparation and curing of concrete which confirming to BIS: 456-2000 [21].

3. 1. 5. Chemical Admixture

Commercially available Master Gelenium SKY 8233 super-plasticizer (SP) of specific gravity 1.08 has been used to improve workability, mechanical, and durability properties, which was high range water reducing admixture supplied by BASF, Chennai.

3. 1. 6. Alkali Resistant Glass Fibers

Alkali Resistant glass fibers were added in the production of concrete at different percentages and characteristics of fibers were given in Table 3. It was a lightweight and high tensile material, which was evaluated as per ASTM C1579 [22].

TABLE 2. Sieve analysis of natural aggregates and sand

Size of aggregate (mm)	Percentage of aggregates produced
Natural aggregate	
20	3.2
16	4.1
12.5	34.4
10	44.1
4.75	14.2
Sand	
4.75	4.8
2.36	12.8
1.18	49.6
600	11.6
300	16.4
150	4
Pan	0.8

TABLE 3. Characteristics of alkali-resistant glass fibers

Characteristics	
Specific gravity	2.68
Density	2.7
Elastic modulus (Gpa)	72
Tensile strength (Mpa)	1700
Fiber filament diameter (microns)	14
Length (mm)	12

3. 2. Methodology

3. 2. 1. Mix Proportions In the present study, M30 grade concrete mix was designed based on the specifications BIS: 10262-2009 [23], BIS: 456-2000 [21], and SP: 29 [24]. Various trials have been performed to fix the correct dosage of super-plasticizer with respect to water reduction and optimum level of cement replacement by GGBFS, silica fume with the addition of glass fibers to attain desired target strength. The various mix combinations were given in Tables 4-7.

3. 2. 2. Samples Preparation In this part, the materials were mixed properly in a tilting type mixer machine until the concrete attained uniform consistency. Thoroughly mixed concrete as shown in Figure 1(a) was compacted into the required molds in three equal layers (casting) as shown in Figure 1(b) and de-molded after 24 hours, followed by curing in water for 7 and 28 days as shown in Figure 1(c) and then tested at room temperature. The cube specimens of size 100 x 100 x 100 mm were used to conduct the compressive strength, water absorption test, and ultrasonic pulse velocity test. Similarly, the cylindrical specimens of size 200 x 100 mm were used to test split tensile strength and beam specimens of size 500 x 100 x 100 mm were used to test flexural strength.

4. RESULTS AND DISCUSSIONS

Initially to fix the optimum replacement of OPC by GGBFS, SF with the addition of GF various trials to be conducted as follows. Further, CC, HCRC, and GFC were tested with different properties, mix proportions of different concrete were given in Table 8.

TABLE 4. Mixture compositions with super-plasticizer content with water reduction and 7days Compressive strength

Mix ID	Mix Combinations	OPC (kg/m^3)	Water (kg/m^3)	Sand (kg/m^3)	Natural aggregate (kg/m^3)	SP (kg/m^3)	7 Days Strength (MPa)
C0	0%S.P Control	438	197.2	640	1077	-	27
C1	0.1%S.P(16%WR)	369	166	690	1161	0.369	۲۲,۷
C2	0.2%S.P(16%WR)	369	166	690	1161	0.738	24
C3	0.3%S.P(16%WR)	369	166	690	1161	1.107	24.8
C4	0.4%S.P(16%WR)	369	166	690	1161	1.476	23.1
C5	0.5%S.P(16%WR)	369	166	690	1161	1.845	22.9
C6	0.1%S.P(19%WR)	356	160	701	1179	0.356	22.7
C7	0.2%S.P(19%WR)	356	160	701	1179	0.712	27
C8	0.3%S.P(19%WR)	356	160	701	1179	1.068	27.4
C9	0.4%S.P(19%WR)	356	160	701	1179	1.424	26.9
C10	0.5%S.P(19%WR)	356	160	701	1179	1.78	25.9
C11	0.1%S.P(21%WR)	346	156	707	1191	0.346	22.1
C12	0.2%S.P(21%WR)	346	156	707	1191	0.692	23.7
C13	0.3%S.P(21%WR)	346	156	707	1191	1.038	21.3
C14	0.4%S.P(21%WR)	346	156	707	1191	1.384	26.9
C15	0.5%S.P(21%WR)	346	156	707	1191	1.73	27.6
C16	0.6%S.P(21%WR)	346	156	707	1191	2.076	26.6
C17	0.7%S.P(21%WR)	346	156	707	1191	2.422	23.5

TABLE 5. Mixture compositions with GGBFS as cement replacement with 7days compressive strength

Mix ID	Mix Combinations	OPC (kg/m^3)	GGBFS (kg/m^3)	Water (kg/m^3)	Sand (kg/m^3)	Natural aggregate (kg/m^3)	SP (kg/m^3)	7 Days Strength (MPa)
CG1	0.4%S.P+90C+10G(21%WR)	311.4	34.6	156	707	1191	1.384	26.3
CG2	0.4%S.P+80C+20G(21%WR)	276.8	69.2	156	707	1191	1.384	25.1
CG3	0.4%S.P+70C+30G(21%WR)	242.2	103.8	156	707	1191	1.384	25.6
CG4	0.4%S.P+60C+40G(21%WR)	207.6	138.4	156	707	1191	1.384	29.1
CG5	0.4%S.P+50C+50G(21%WR)	173	173	156	707	1191	1.384	28.8
CG6	0.4%S.P+40C+60G(21%WR)	138.4	207.6	156	707	1191	1.384	24.8
CG7	0.5%S.P+90C+10G(21%WR)	311.4	34.6	156	707	1191	1.73	27.9
CG8	0.5%S.P+80C+20G(21%WR)	276.8	69.2	156	707	1191	1.73	28.6
CG9	0.5%S.P+70C+30G(21%WR)	242.2	103.8	156	707	1191	1.73	28.5
CG10	0.5%S.P+60C+40G(21%WR)	207.6	138.4	156	707	1191	1.73	28.9
CG11	0.5%S.P+50C+50G(21%WR)	173	173	156	707	1191	1.73	29.9
CG12	0.5%S.P+40C+60G(21%WR)	138.4	207.6	156	707	1191	1.73	24.9

TABLE 6. Final Optimum Mixture compositions with GGBFS and silica fume as cement replacement

Mix ID	Mix Combinations	OPC (kg/m^3)	GGBFS (kg/m^3)	SF (kg/m^3)	Water (kg/m^3)	Sand (kg/m^3)	Natural aggregate (kg/m^3)	SP (kg/m^3)	7 Days Strength (MPa)
CGS1	0.5%S.P+49C+50G+1SF	171.27	173	1.73	156	707	1191	1.73	29.8
CGS2	0.5%S.P+48C+50G+2SF	169.54	173	3.46	156	707	1191	1.73	30.2
CGS3	0.5%S.P+47C+50G+3SF	167.81	173	5.19	156	707	1191	1.73	31.2
CGS4	0.5%S.P+46C+50G+4SF	166.08	173	6.92	156	707	1191	1.73	29.1
CGS5	0.5%S.P+45C+50G+5SF	164.35	173	8.65	156	707	1191	1.73	27.9

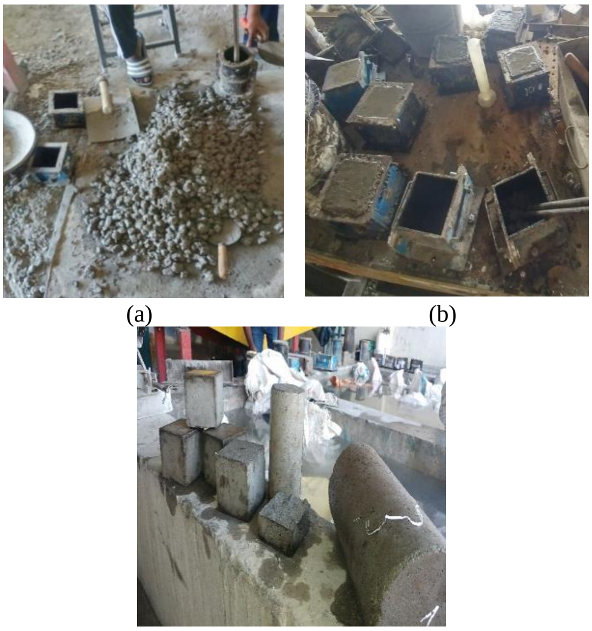
TABLE 7. Final Optimum Mixture compositions with GGBFS and silica fume as cement replacement with glass fibers

Mix ID	Mix Combinations	OPC (kg/m^3)	GGBFS (kg/m^3)	SF (kg/m^3)	Water (kg/m^3)	Sand (kg/m^3)	Natural aggregate (kg/m^3)	SP (kg/m^3)	GF (kg/m^3)	7 Days Strength (MPa)
CGSF1	0.5%S.P+47C+50G+3SF+0.1%GF	167.81	173	5.19	156	707	1191	1.73	2.4	28.9
CGSF2	0.5%S.P+47C+50G+3SF+0.2%GF	167.81	173	5.19	156	707	1191	1.73	4.8	29.7
CGSF3	0.5%S.P+47C+50G+3SF+0.3%GF	167.81	173	5.19	156	707	1191	1.73	7.2	27.3

4. 1. Optimizing the Dosage of SP and Replacements with Different Materials

4. 1. 1. Optimizing Dosage of SP with Respect to Water Reduction

The water-reducing admixture SP was considered in the mix design to reduce the cement content in concrete. To get the optimum mix, various mix combinations with different percentages of super-plasticizer with respect to different water reduction percentages were tested with 7 days compressive strength and given in Table 4. Among 18 mix combinations (C0 to C17), the highest compressive strength was obtained for C14 and C15 mix of 26.9 and 27.6 MPa which was higher than the control concrete (C0) as 27 MPa. Similarly, the lowest compressive strength of 21.3 MPa was obtained for C13 mix which was lower than the control concrete (C0) as presented in Table 4.



(a) (b) (c)

Figure 1. (a) Fresh concrete, (b) Casting specimens, (c) Curing specimens

4. 1. 2. Optimizing OPC Replacement with GGBFS The optimum mixes C14 and C15 were taken and cement replaced with GGBFS at different percentages from 10 to 60% (CG1 to CG12) as given in Table 5. The highest 7 days compressive strength of 29.9 MPa was achieved for CG11 mix which was 8.3% more than C15 control mix. As the cement replacement by GGBFS at all the levels the compressive strength was obtained higher. From the results, it was observed that 50% replacement with GGBFS was optimum which obtained the desired strength.

4. 1. 3. Optimizing OPC Replacement with GGBFS and SF The optimum mix CG11 was selected from Table 6 and OPC has been replaced with SF from 1 to 5% (CGS1 to CGS5). The highest 7 days compressive strength of 31.2 MPa was achieved at 3% SF (CGS3) which was 4.3% more than CG11 mix.

The finer size of SF with high pozzolanic nature was responsible to achieve good strength. Hence, it was observed that using 50% GGBFS and 3% SF replacement will attain the desired target strength.

4. 1. 4. Optimizing OPC Replacement with GGBFS and SF with the Addition of GF The optimum mix CGS3 was taken and added GF at 0.1 to 0.3% (CGSF1 to CGSF3) by the total volume of concrete is given in Table 7. The highest 7 days compressive strength was noted 29.7 MPa at 0.2% glass fibers which were higher than the CC.

4. 2. Compressive Strength The 7, 28 days compressive strengths of different types of concrete were tested by a universal testing machine as shown in Figure 2(a) and the results were given in Table 9. It was noticed that the HCRC mix showed higher compressive strength than CC, because of high CaO and less Al_2O_3 content which results in from a pozzolanic reaction. The compressive strength of HCRC and GFC was slightly higher around 2% than CC but with the addition of GF, 1% declined in compressive strength was observed. Compressive strength values were decreased for OPC replacement beyond the optimum percentage because of escaping out of excess lime that leads to a decline in pore bonding strength [25–28].

4. 3. Split Tensile Strength The split tensile test was performed as per BIS: 516-1959 [29] in a universal testing machine as shown in Figure 2 (b) and the strength value of different mixes were shown in Table 9. From the results, it was noticed that the positive influence of glass fibers on split tensile strength. The highest split tensile strength of 4.73 MPa was observed for the GFC mix and lowest for CC mix of 4.12 MPa. With respect to CC mix tensile strength was increased by about 11% for HCRC mix and 14.8% for GFC mix at 28 days. With addition of 0.2% GF in HCRC mix 3.5 % more split tensile strength was achieved for the GFC mix. By replacing OPC with GGBFS, SF, the interfacial transition zone (ITZ) becomes solid which results in the enhancement of tensile strength [12, 26]. The GF used in the present study has 6-12 mm length which increases the resistance of concrete against splitting. A similar performance of GF at an optimum dosage has been noted in earlier studies [30].

TABLE 8. Final optimum Mixture compositions with GGBFS, SF with GF

Mix ID	Mix Combinations	OPC (kg/m^3)	GGBFS (kg/m^3)	SF (kg/m^3)	Water (kg/m^3)	Sand (kg/m^3)	Natural aggregate (kg/m^3)	SP (kg/m^3)	GF (kg/m^3)
*CC	0%S.P+100C	438	-	-	197.2	640	1077	-	-
HCRC	0.5%S.P+47C+50G+3SF	167.81	173	5.19	156	707	1191	1.73	-
GFC	0.5%S.P+47C+50G+3SF+0.2GF	167.81	173	5.19	156	707	1191	1.73	4.8

(a) (b)

Figure 2. (a) Compressive strength, (b) Split tensile strength

4. 4. Flexural Strength Flexural strength test was conducted as per BIS: 516-1959 [29] in the flexural testing setup as shown in Figure 3 and the values of various mixes were presented in Table 9. It was observed from the results that the highest flexural strength of 6.03 MPa for GFC mixes and lowest of 4.91 MPa for CC mix at 28 days. With respect to CC mix, flexural strength was increased by about 18.3% for the HCRC mix and 22.8 % for the GFC mix. With addition of 0.2% GF in HCRC mix, 3.8 % more flexural strength was attained for the GFC mix. From the above results, the utilization of GGBFS, SF, and GF enhanced the strength for all mixes, in comparison with the CC mix.

4. 5. Water Absorption The water absorption test was conducted as per ASTM C642-2013 [31], by oven dry process after 7, 28 days of specimen curing as shown in Figure 4. The effect of GGBFS, silica fume with glass fibers on the water absorption presented in Figure 5. The highest water absorption was observed for CC mix as 2.4% and lowest for GFC mix as 1.95%. From the results, it was noticed that the HCRC and GFC mixes show 11.7 and 18.7% lesser water absorption than CC mix. Similarly, the GFC mix shows 8% lesser water absorption value than the HCRC mix. The above test results show that lower water absorption values have higher compressive strengths. The lower water absorption may occur because of higher pozzolanic effect by GGBFS and SF which results in a decrease in pore structure to produce denser concrete [4, 5].

Figure 3. Flexural strength

Figure 4. Water absorption test

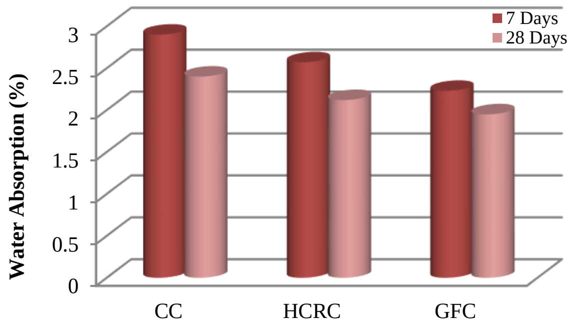


Figure 5. Water absorption values

TABLE 9. Mechanical properties of Final optimum mixtures

Mix Type	Compressive Strength (MPa)		Split Tensile Strength (MPa)		Flexural Strength (MPa)	
	7 Days	28 Days	7 Days	28 Days	7 Days	28 Days
CC	27.0	38.9	3.26	4.12	3.67	4.91
HCRC	31.2	39.7	3.18	4.57	4.19	5.81
GFC	29.7	39.3	3.28	4.73	4.52	6.03

4. 6. Ultrasonic Pulse Velocity Ultrasonic pulse velocity (UPV) test was an indicator to check the homogeneity of concrete in the form of porosity and permeability as per BIS: 13311(1) – 1992 [32] as shown in Figure 6. A higher UPV value was generally related to a solid structure of concrete, in which all the results show excellent quality. The UPV values for different mixes at 7, 28 days was represented in Figure 7. The UPV values for HCRC and GFC mixes were higher than CC mix at 7 and 28 days which exhibit an excellent quality of concrete. From the results, it was observed that GGBFS, SF have lesser specific gravity than OPC which helps the concrete to form dense structure results in enhancement of characteristics of concrete.

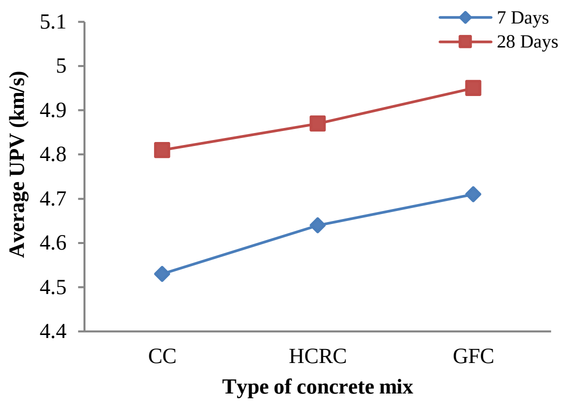


Figure 7. Average ultrasonic pulse velocity values

4. 7. Cost Analysis In this study, the different concrete mixes were produced with the replacement of OPC by GGBFS, SF with addition of GF. So, this section aims to study the entire cost obtained in the production of CC, HCRC, and GFC mixes. The mixes were compared with each other with the available market prices of various materials used in the production of concrete. The cost of various mixes presented in Table 10 was calculated for one meter cube based on the quantity of materials as per the final mix design. Based on the results, the CC mix is costlier than HCRC and FRC mixes. The highest cost savings in the production of CC to HCRC mix is 26% and followed by CC to FRC mix is 18.3%. Therefore, concrete production with HCRC and GFC mix will have ecological and economical benefits in practice.


Figure 6. UPV test

TABLE 10. Materials and cost per meter cube of concrete for different mixes

Mixture ID		CC		HCRC		GFC	
Materials	Cost per kg (US $)	Materials and cost per m^3		Materials and cost per m^3		Materials and cost per m^3	
		Materials (kg)	Cost (US $)	Materials (kg)	Cost (US $)	Materials (kg)	Cost (US $)
OPC	0.10	438	43.8	167.81	16.78	167.81	16.78
GGBFS	0.029	-	-	173	5.02	173	5.02
SF	0.11	-	-	5.19	0.57	5.19	0.57
Sand	0.0066	640	4.23	707	4.67	707	4.67
Natural Aggregate	0.013	1077	14.0	1191	15.48	1191	15.48
SP	1.98	-	-	1.73	3.42	1.73	3.42
GF	0.99	-	-	-	-	4.8	4.75
Water	0.0013	197.2	0.26	156	0.20	156	0.20
Cost of concrete per m^3 (US $)			62.29		46.14		50.89

5. CONCLUSIONS

Based on the experimental investigations carried out on different mixes, the following conclusions were drawn.

1. So many trials were conducted to fix the correct dosage of super-plasticizer with respect to water reduction percentage before utilizing in the mass concrete applications.

2. To achieve the desired target strength, an optimum of 0.5% of SP with 21% water reduction was used in the entire study.
3. By utilizing the combination of GGBFS, SF, and GF had improved the particle filling and pore structure which tends to the enhancement of all the concrete properties.
4. The higher test results were observed with the mix containing 50% GGBFS, 3% SF and 0.2% GF. Because of the higher specific surface area of materials have high pozzolanic action which results in C-S-H gel which helps in improving the concrete properties.
5. The cost to produce HCRC mix reduces to 26% when compared with CC mix. Similarly, the cost to produce FRC mix reduces to 18.3% when compared with CC mix.
6. Utilizing the combination of GGBFS and SF at high percentages as a substitute for OPC produces ecological and sustainable concrete.

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Persian Abstract

چکیده

تمرکز استفاده از بتن‌های ترکیبی در ساخت و توسعه ساختمان‌ها، بزرگراه‌ها و سایر سازه‌های مهندسی عمران می‌باشد. در مطالعه حاضر، طرح مخلوط‌های متفاوتی از بتن‌های ترکیبی با درصدهای مختلف فوق روان‌کننده، مقادیر مختلف درصد آب جهت تعیین طرح بهینه در آزمایشگاه مورد بررسی قرار گرفته است. همچنین جایگزینی سیمان پرتلند معمولی با الیاف شیشه، دوده سیلیسی و سرباره کوره آهن‌گدازی به منظور حصول نتیجه بهینه و دریافت بتن با سیمان جایگزین شده نیز مورد بررسی قرار گرفت. در نهایت عملکرد بتن تولید شده توسط تست اسلامپ، تست مقاومت فشاری، تست مقاومت کششی، تست مقاومت خمشی، تست جذب آب و تست پالس اولتراسونیک مورد ارزیابی قرار گرفت. نتایج حاصله بیانگر عملکرد بهینه بتن ترکیبی در صورت استفاده از ۵۰٪ سرباره کوره آهن‌گدازی و ۳٪ دوده سیلیسی بوده است. همچنین در صورت استفاده از ۰/۲ ٪ الیاف شیشه، عملکرد کششی و خمشی بتن به طور قابل توجهی در تمامی سنین بهبود پیدا کرده است. در نهایت نشان داده شد که عملکرد بتن ترکیبی پیشنهادی به مراتب نسبت به بتن مرجع بهتر بوده است.