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Sustainable High-performance Concrete for Transportation Infrastructure Developments

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Abstract: One of the key technologies for achieving sustainable concrete construction is the development of carbon-neutral or green concrete. The goal of creating zero-carbon concrete is a long-term endeavor. Currently, numerous efforts are underway to produce Portland cement materials with a reduced carbon footprint in their production. This paper discusses the development of high-performing concrete, specifically high early-strength concrete, utilizing environmentally friendly hydraulic cement (based on Indonesian Standard, SNI 8912: 2020) manufactured by PT. Semen Indonesia (Persero) Tbk. The concrete mixture is designed according to the key performance indicators established for high early-strength concrete, which include a flexural strength of 4.50 MPa at three days of age, an initial slump of 20.0 ± 2.0 cm, and an initial setting time of 8.0 hours. The hydraulic cement used is labeled HCN and HCT. Normal Ordinary Portland Cement (OPC) serves as a baseline for standard OPC concrete. Two types of concrete admixtures are employed to optimize the dosage in the concrete mixture to control the development of high strength and workability parameters, ensuring that the key performance indicators are met. Trials of concrete mixtures with a low water-to-cement ratio are conducted, with a maximum cement content of 500 kg per m^3 of concrete mixtures. The results indicate that, in general, trial concrete mixtures based on hydraulic cement can meet the key performance indicators established for the formulation of high early-strength concrete. Specifically, it has been found that the hydraulic cement-based concrete mixture labeled HCN, with cement-to-water ratios of 0.28 and 0.30, performs the best, achieving the targeted key performance indicator while reducing CO2 emissions by up to 13.64% compared to the OPC-based concrete.

Keywords: Hydraulic Cement; Admixtures; High Early Strength Concrete; Flexural Strength; Slump Value

1. Introduction

Like many nations, Indonesia aims to contribute to global efforts in limiting global temperature rise and mitigating climate change impacts by reducing carbon emissions in line with the Paris Agreement by the United Nations Framework Convention on Climate Change (UNFCCC), which was the first international treaty at addressing climate change action, adopted at the Paris climate conference (COP21) in December 2015[1,2]. Modern society utilizes concrete materials in massive amounts, more than all other materials apart from water[3]. However, the extensive use of concrete has a detrimental impact on carbon dioxide emissions (CO_2e), due to production processes. Concrete production involves significant energy and releases substantial CO_2e, contributing to environmental degradation and climate change. The use of concrete embodied CO_2e, such as ordinary Portland cement (OPC) based-concrete in transportation infrastructure developments should be necessarily in a warning condition, since the OPC-based concrete releases CO_2e during the production, transportation, and construction of concrete materials. The widespread use of concrete, with its embodied carbon dioxide emissions (CO2e), challenges the goals outlined in the United Nations Framework Convention on Climate Change (UNFCCC) Paris Agreement**.** The Agreement aims to limit global temperature increase to well below 2 degrees Celsius above pre-industrial levels[1,2)]. Excessive concrete usage intensifies carbon footprints, hindering efforts to achieve the Agreement's targets and exacerbating climate change concerns[4)]. Sustainable construction practices and materials are imperative to align with the Agreement's commitment to mitigating climate impacts, as stated previously. Addressing embodied CO_2e in concrete typically involves a combination of national policies, industry practices, and technological advancement to align with broader climate objectives. In this work, the technological effort is attempted to produce concrete materials with lesser CO_2e, by lowering clinker factors in cement production[15)].

The transition from traditional ordinary Portland cement (OPC) to lower clinker hydraulic cement represents a significant shift in the construction industry's quest for sustainability and reduced environmental impacts. This transformation is driven by the need to curtail carbon emissions associated with clinker production, the primary contributor to OPC's environmental carbon footprint. The OPC production is responsible for about 5–8% of man-made CO_2 emissions[4,5,34,35)]. Lower clinker hydraulic cement, including but not limited to Portland limestone cement (PLC), Portland pozzolana cement (PPC), and Portland composite cement (PCC), offer a promising alternative with their lower clinker content, improved performance characteristics, and a reduced carbon footprint[6,35,42)]. This introduction explores the motivations, benefits, and challenges associated with this pivotal change in the world of cement and concrete. Hydraulic cement is a type of cement that can harden and set underwater. It is commonly used in construction, including in the production of concrete. An effort that could be made is to develop low-carbon concrete mix designs based on new hydraulic cement-based concrete. The use of hydraulic cement in concrete structures can contribute to reducing the carbon embodied in concrete materials, therefore it is just one part of a broader strategy to make the construction industry greener and more environmentally friendly. Other factors such as using recycled materials, optimizing concrete mix designs, and finding alternative binders to traditional cement can also play significant roles in achieving a carbon emission reduction in construction industries. A decarbonization initiative related to greenhouse gas (GHG) that attempted by the PT. Semen Indonesia (Persero) Tbk. includes increasing alternative fuel and raw material use, reducing clinker factor in cement production, and optimization of specific thermal energy consumption Therefore, the so-called green concrete could be established or at least concrete embedded CO_2e could be reduced in construction industries[7,37,41)].

The concrete-based construction industry in Indonesia has consumed a massive amount of concrete. In particular, the development of transportation infrastructures and connectivity in recent years has been directed to the areas of transportation infrastructure sectors, as depicted in Table 1. As seen in Table 1, the land, sea, and air transportation infrastructures often necessitate a substantial amount of concrete for building durable and robust structures like roads, bridges, ports, and runways. It is estimated that in the year 2023, the development sector in the Ministry of Public Work and Public Housing (MPWPH) requires approximately 5.659.000 tons of cement for various national infrastructure development programs[8)].

Table 1. Transportation Infrastructures Directives[8,9)].

No	Policy Direction of Supportive Regional Development
Land Transportation – Road Infrastructures	
1	Completion of the construction of the Trans Sumatra Toll Road
Land Transportation – Rail Road Infrastructures	
2	Development of a freight railroad network for goods access to the Port
3	Construction of intercity railways in stages
Sea Transportation	
4	Port Development in Belawan-Kuala Tanjung, Dumai, and Batam.
5	Construction of a domestic transit hub port in the Maluku Region to improve intra-archipelago connectivity
Air Transportation	
6	Development of major airports and integration with its regional developments

Based on SIG experiences using the method of World Business Council for Sustainable Development (WBCSD) protocol 3.1[10,11)], the manufacture of ordinary Portland cement (OPC) will supply 814 kg CO_2 emission per ton of OPC production, whilst the hydraulic cement (HC) with a lower clinker factor will reduce to that of OPC to 703 kg per ton of HC production The comparison between concrete based OPC and HC about the potential amount of CO_2e, can be seen in Table 2.

Table 2. Potentially CO_2e produced by cement needs.

Type of Cement	CO_2e per ton cement production (kg/ton)	MPWPH Cement needs in 2023 (ton)	Amount of CO_2e produced (ton)
OPC	814	5.659.000	4.606.426
HC	703	5.659.000	3.978.277

As seen in Table 2, ordinary Portland cement (OPC) produced 15.8 % CO_2e higher compared to the hydraulic cement (HC) used in this work. However, the answer needs to know how the lower clinker factor cement could be used and designed to produce concrete with a lesser embodied CO_2e as high-performance concrete[51,52,54,55], in particular as a high early strength concrete (HESC).

While significant advancements have been made in the development of Portland cement materials with reduced carbon footprints, the quest for creating carbon-neutral or green concrete remains an ongoing challenge. Existing studies have primarily focused on the production of constructional concrete with lower CO_2 emissions[46-50]. However, there is a noticeable lack of research on the development and performance evaluation of high early-strength concrete using environmentally friendly hydraulic cement, particularly within the context of specific regional standards like the Indonesian Standard (SNI 8912: 2020). This paper aims to bridge this gap by investigating the performance of high early-strength concrete mixtures using hydraulic cement produced by PT. Semen Indonesia (Persero) Tbk, and assessing their ability to meet established key performance indicators while reducing carbon emissions. The findings from this study can contribute to the broader effort of achieving sustainable concrete construction through the development of high-performing, low-carbon concrete alternatives. In this paper, the concrete mixture formulation is developed using the hydraulic cement manufactured by the PT. Semen Indonesia (Persero) Tbk., based on Indonesian Standard, SNI 8912:2020.

2. Material and Method

The research gaps identified in this study highlight several key areas that require further exploration. While the transition from Ordinary Portland Cement (OPC) to lower clinker hydraulic cement is recognized as essential for reducing carbon emissions, there is a notable lack of research focused on designing high early strength concrete (HESC) that effectively balances reduced CO_2e with performance requirements. Most existing studies emphasize the environmental benefits of lower clinker cement but do not sufficiently address how these materials can be optimized for high early-strength applications, particularly in critical infrastructure projects[53,56-58].

Additionally, there is an insufficient exploration of the optimal mix designs for hydraulic cement that achieve both low carbon footprints and high performance, especially in the context of large-scale infrastructure projects. This gap in research limits the potential for hydraulic cement to serve as a sustainable alternative to OPC in high-stakes construction projects. Moreover, while the environmental impact of different cement types is often discussed, there is a significant lack of data and case studies on the practical application and performance of hydraulic cement-based concretes in real-world infrastructure projects. This absence of field data and performance analysis constrains the understanding of how these materials perform under the specific conditions encountered in large transportation infrastructure projects.

To address these gaps, this paper develops a concrete mixture formulation using hydraulic cement with reduced clinker content, specifically targeting high early strength performance. The concrete mixtures are designed following the Indonesian Standard (SNI 8912:2020) and are evaluated for both their CO2e emissions and early strength performance. The method also involves comparing the CO2e emissions and performance characteristics of the newly developed hydraulic cement-based concretes with traditional OPC-based concretes, demonstrating the viability of hydraulic cement as a more sustainable alternative in the construction industry.

2.1 Materials

Concrete is a composite material made up of various ingredients that work together to provide its structural and functional properties. The main basic material ingredients of concrete include cement, fine and coarse aggregates, water, admixture, and other mixture materials[20,21].

2.1.1 Concrete Ingredient

The concrete ingredient considered to be used in the concrete mixture design herein has the chemical composition and characteristics that will be described in the following section.

2.1.1.1 Cement

Three types of cement are used: Ordinary Portland cement (OPC) and two types of Hydraulic cement (HC). X-ray diffraction (XRD) measurements of the cements are as follows:

Table 3. XRD Measurement of Cements Used.

XRD Measurement	**Unit**	**Type of Cement**		
		OPC	**HCT**	**HCN**
C3S<M1>	%	24,48	30,06	20,02
C3S<M3>	%	27,01	17,86	27,10
C2S_beta	%	13,83	8,45	9,77
C2S alpha	%	0,63	0,24	0,80
C2S alpha H	%	1,73	1,58	0,76
C2S gamma	%	0,29	1,28	0,18
C3A_cubic	%	4,95	6,04	4,26
C3A_orthorhombic	%	0,49	0,34	0,39
C3A monoclinic	%	0,00	0,00	0,59
C4A F-A	%	4,38	2,97	3,96
C4A F-B	%	6,76	5,10	5,51
Lime	%	0,18	0,36	0,07
Periclase	%	0,41	0,65	0,60
Portlandite	%	0,52	2,37	0,91
Quartz	%	0,34	0,23	2,77
Arcanite	%	0,11	0,32	0,22
Thernadite	%	0,73	-	0,97
Langbeinite	%	0,20	0,65	-
Aphthitalite	%	0,60	0,01	0,54

Gypsum	%	1,34	0,34	1,24
Basanite	%	1,06	2,68	0,72
Anhydrite	%	0,18	0,13	0,12
Calcite	%	9,40	9,17	12,54
Dolomite	%	0,07	2,53	0,19
Syngenite	%	0,09	0,32	0,13
Andesine An50	%	-	5,73	-
Dawsonite	%	-	0,30	0,59
Actinolite	%	-	0,29	-
Amorphous_Phase	%	0,24	-	5,06
Total Clinker	%	87,65	79,86	78,83
Filler (Limestone)	%	9,47	11,79	12,72
Gypsum	%	2,58	2,32	2,08
Pozzolan	%	0,29	6,03	7,83

XRD analysis is a technique used to determine the atomic and molecular structure of a material, such as a crystal or powder. The XRD analysis of cement[31)] can provide information about its mineral composition. Table 3 depicts the mineral composition of cement used herein, i.e. OPC is ordinary Portland cement; the HCT and the HCN are the codes for two hydraulic cements. The main common phases identified herein in cement XRD patterns include C3S (Tricalcium Silicate) as the main phase responsible for early strength development, C2S (Dicalcium Silicate) which contributes to the strength of the cement, C3A (Tricalcium Aluminate) as a phase that influences setting time and C4AF (Tetracalcium Aluminoferrite) which plays a role in the heat evolution during hydration. Other potential phases might include Lime (Calcium Oxide) which is often present in cement, Periclase (Magnesium Oxide) which might be from impurities or additives and Portlandite (Calcium Hydroxide) which forms during the hydration process. Furthermore, in the context of cement chemistry, C3S<M1> and C3S<M3> refer to different polymorphs or modifications of Tricalcium Silicate (C3S), which is one of the main components of Portland cement clinker. The C3S<M1> is the monoclinic form of Tricalcium Silicate. It is the stable form of C3S at temperatures below approximately 1250° C during the clinker manufacturing process. Monoclinic C3S has different crystallographic properties compared to the high-temperature form C3S<M3>. It transforms into C3S<M3> at higher temperatures. Whilst, C3S<M3> is the triclinic form of Tricalcium Silicate. At temperatures above 1250° C, C3S undergoes a phase transition from the monoclinic form C3S<M1> to the triclinic form C3S<M3>. This transformation is a part of the clinker formation process in cement production. Understanding the different polymorphs of C3S is important in cement chemistry because the properties of these phases influence the hydration process of cement and, consequently, the strength development and other characteristics of the resulting concrete[20,21)]. The transformation between these polymorphs is crucial during the cooling stage of the clinker production[31,32)].

As can be seen in Table 3, the overall clinker for the hydraulic cement of HCN and HCT which are 78.83% and 79.86% respectively are less than the overall clinker of the OPC which is 87.65%, in other words, the clinker for hydraulic cement is lower than the OPC one, therefore it is expected that the manufacture of hydraulic cement gives less CO_2e compared to the OPC[41-43)].

The chemical composition of the Ordinary portland cement (OPC) and hydraulic cement (HCT and HCN) based on Indonesian Standard SNI 2049: 2015 (Type I) and SNI 8912: 2020 respectively, in this work can be seen in Table 4, as follows:

Table 4. Chemical Composition of Cements.

Parameter	Unit	SNI OPC	SNI HC	Type of Cement		
		SNI 2049 : 2015 (Type I)	SNI 8912: 2020	OPC	HCT	HCN
Chemical Composition:						
S_iO_2	%	-		18,84	20,39	20,07
Al_2O_3	%	-		5,45	5,58	6,23
$F_{e2}O_3$	%	-		3,32	2,43	3,69
CaO	%	-		64,38	56,35	58,12
MgO	%	Max. 6.00	Not required	1,42	2,57	1,70
SO_3	%	Max. 3.50		1,64	1,79	1,41
Lost on Ignition	%	Max. 5.00		4,51	5,97	7,49
Free lime	%			1,32	2,24	1,88
Insoluble part	%	Max. 3.00		1,13	5,57	7,26

2.1.1.2 Aggregates

The concrete aggregates used in this work comprise the natural fine and coarse aggregates. The particle size gradation of fine and coarse aggregates is measured by sieve analysis based on ASTM C136 standard: Sieve or Screen analysis of fine and coarse aggregates[25)]. The natural fine aggregate that was used in the concrete mixture was Silica sand and in this work has grain sizes of 0.0 mm to 5.0 mm as depicted in Fig. 1. Sieve analysis is a widely used method for determining the particle size distribution of aggregates in concrete mix design. The purpose of this analysis is to ensure the aggregates used in concrete are well-graded, meaning they have a distribution of particle sizes that allows for optimal packing and improves the workability and strength of the concrete.

Fig. 1: Silica sand fine aggregate (0.0 – 5.0 mm).

The sieve analysis of fine aggregates was carried out and it conforms to the standard of ASTM 136 test method [25)]. The sand used has a grain size not exceeding 5 mm, a specific gravity of 2.62, and a unit weight of 1320 kg/m^3. The fine aggregate grading resulting from the sieve analysis can be seen in Table 5 and Fig. 2. As depicted in Table 5 as well as in Fig. 2, the grain size distribution of fine aggregate used can be considered to be a well-graded grain size distribution of fine aggregates.

Table 5. The result of fine aggregate sieve analysis.

ASTM SIEVE		Weight Retained	Accumul Retained	Accumul Retained	Passing	Specification ASTM C33	
Inch/No	mm	(gr)	(gr)	(%)	(%)	min	max
3/8 "	9,5	0	0	0,0	100,0	100,0	100,0
# 4	4,75	4,7	4,7	0,9	99,1	95,0	100,0
# 8	2,36	51,2	55,9	11,2	88,8	80,0	100,0
# 16	1,18	92,3	148,2	29,6	70,4	50,0	85,0
# 30	0,60	150,4	298,6	59,7	40,3	25,0	60,0
# 50	0,30	89,7	388,3	77,7	22,3	5,0	30,0
# 100	0,15	79,3	467,6	93,5	6,5	0,0	10,0
# 200	0,075	21,7	489,3	97,9	2,1	0,0	0,0
PAN		10,7	500	100,0	0,0		
TOTAL							
FM				2,727			
Additional Test							
Parameter			Unit	Result			
Specific Gravity (ssd)				2,62			
Absorption			%	1,07			
Material finner Than 75 micron			%	3,66			
Unit Weight			ton/m^3	1,32			
Organic Impiurities			No	3			

The particle size distribution curve of fine aggregate using cumulative percentage passing tested by ASTM C 136[25)] can be seen in Fig. 2.

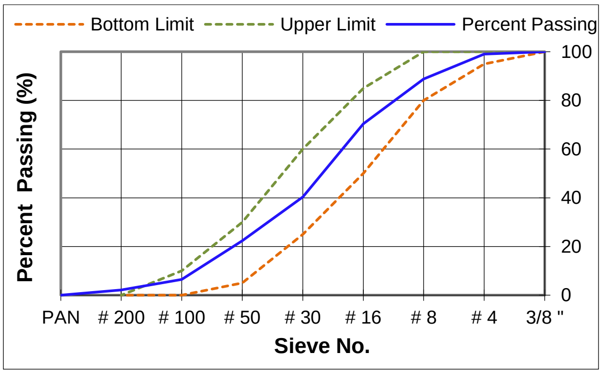


Fig. 2: Particle size distribution of fine aggregate.

As can be seen in Fig. 2. The particle size distribution of fine aggregates used fits well within the upper and lower limits of the ASTM C136[25)] Standard for sieve or screen analysis of fine and coarse aggregates.

The coarse aggregate used in this work was made from crushed stone with a size of 10.0 -20.0 mm. Tests are carried out to check the coarse aggregate gradation specifications according to the ASTM standard C 136[25)]. Figure 3 shows the sieve analysis results and Table 4 demonstrates some of its physical characteristics. As seen in Fig. 3, the particle size distribution of coarse aggregates employed in this work falls rather outside the lower limits of the ASTM C136 standard[25)] and there is no effort carried out to improve for the betterment of the coarse aggregate size distribution.

2.1.1.3 Water

The water used as one of the ingredients of concrete was fresh, dirt-free water.

Fig. 3: The coarse aggregates (10.0 – 20.0 mm).

The sieve analysis result and its grain size distribution curve of coarse aggregate can be seen in Table 6 and Fig. 3 respectively.

Table 6. The result of coarse aggregate sieve analysis.

ASTM SIEVE		Weight Retained	Accumul Retained	Accumul Retained	Passing	Specification ASTM C33	
Inch/No	mm	(gr)	(gr)	(%)	(%)	min	max
1 1/2 "	38,1	0	0	0,0	100,0	100,0	100,0
1 "	25	0	0	0,0	100,0	100,0	100,0
3/4 "	19	103,7	103,7	10,4	89,6	90,0	100,0
1/2 "	12,5	786,4	890,1	89,0	11,0	20,0	55,0
3/8 "	9,5	104,7	994,8	99,5	0,5	0,0	15,0
# 4	4,75	0	994,8	99,5	0,5	0,0	5,0
# 8	2,36	0	994,8	99,5	0,5	0,0	0,0
# 16	1,18	0	994,8	99,5	0,5	0,0	0,0
# 30	0,60	0	994,8	99,5	0,5		
# 50	0,30	0	994,8	99,5	0,5		
# 100	0,15	1,3	996,1	99,6	0,4		
# 200	0,075	3,3	999,4	99,9	0,1		
PAN		0,6	1000	100,0	0,0		
TOTAL							
FM		7,069					

Additional Test

Parameter	**Unit**	**Result**
Specific Gravity (ssd)		2,60
Absorption	%	2,24
Material finner Than 75 micron	%	1,08
Unit Weight	ton/m^3	1,45

The particle size distribution curve of coarse aggregate using cumulative percentage passing the sieve can be seen in Fig. 4.

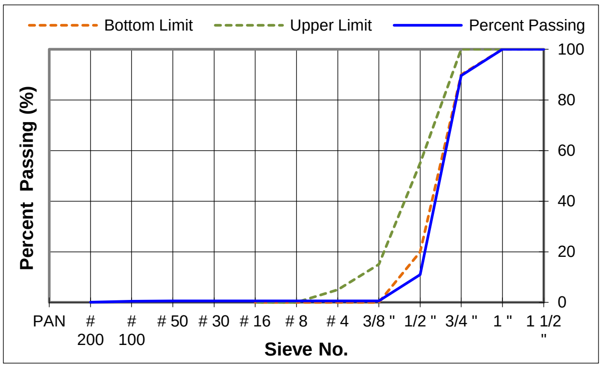


Fig. 4: Particle size distribution of coarse aggregate.

2.1.1.4 Admixture

Admixtures in concrete play a crucial role in optimizing the properties of both fresh and hardened concrete. In fresh concrete, admixtures are added to enhance workability, improve durability, and control the setting time of the concrete mixture. Admixtures can modify the properties of fresh concrete mixtures, such as a slump value, reducing water content, and enhancing the flow ability of concrete mixtures. Whilst in the hardened concrete, admixtures contribute to the overall performance and durability, i.e. it may enhance strength, durability, and resistance to chemical attack. Admixtures like superplasticizers can reduce water content while maintaining workability, leading to increased strength in hardened concrete[20,21]. In this work, two types of admixtures were used, as follows:

(a) Admixture-1, admixtures consisting of retarders that are categorized as Type F admixture and superplasticizers that are categorized as Type B admixture. The admixture-1 is labeled as AD1.

(b) Admixture-2, admixture consisting of the retarder and the superplasticizer[24] chemicals which are combined and categorized as Type G admixture. The admixture-2 is labeled as AD2.

The admixtures[22-24] in their containers used in the concrete mix proportioning, can be seen in Fig. 4.

Fig. 5: Admixtures labeled as AD1 and AD2.

Determination of the dosage of admixtures used in the concrete mix proportioning is performed by experimental optimization processes, as such that admixture dosages reach the targeted workability parameters[38,40,44,45].

2.1.2 Experimental design and mix proportion

In this work, the concrete mixture is designed to meet the targeted values for high-performance concrete, i.e. high early strength concrete (HESC), employing hydraulic cement (HC) as well as ordinary Portland cement (OPC). The key performance indicators set up for the fresh and hardened concrete are as follows:

(a) Flexural Strength of 4.50 MPa or 45.0 kg/cm^2 (termed as FS-45) is reached within 3 days of the age of hardened concrete

(b) Minimum workability slump is 20 cm ± 2cm

(c) Slump lost in 120 minutes is 2 cm

(d) The initial setting time is 8 hours

The mix design method of high early-strength concrete used herein is mainly based on experimental optimization. However, the requirement for normal concrete mix design described in the Indonesian Standard, SNI 7656: 2012 is also considered. For the high early strength concrete (HESC) targeted herein, a lower water-to-cement ratio (w/c) is typically used. The w/c of 0.28, 0.30, and 0.32 are attempted and a cement content of 500 kg per m^3 concrete mixture is used. To achieve the key performance indicators described previously, the mixture of concrete with high cement content and lower w/c ratio necessitates the use of a certain dosage of admixture. The proper dosages for a certain type of concrete mixture will be determined by an experimental optimization for fresh concrete parameters, such as flow of fresh concrete mixture, workability slump values, and initial setting time.

The type of concrete mixture coding, incorporating variables; the type of cement, w/c ratios, and type of admixture for cement content of 500 kg per m^3 concrete mixtures can be seen in Table 7, as follows.

Table 7. Type of concrete sample coding.

Age	w/c = 0.28		w/c = 0.30		w/c = 0.32	
	(Cement = 500 kg/m^3)		(Cement = 500 kg/m^3)		(Cement = 500 kg/m^3)	
1 day	OPC AD1	OPC AD2	OPC AD1	OPC AD2	OPC AD1	OPC AD2
	HCT AD1	HCT AD2	HCT AD1	HCT AD2	HCT AD1	HCT AD2
	HCN AD1	HCN AD2	HCN AD1	HCN AD2	HCN AD1	HCN AD2
3 days	OPC AD1	OPC AD2	OPC AD1	OPC AD2	OPC AD1	OPC AD2
	HCT AD1	HCT AD2	HCT AD1	HCT AD2	HCT AD1	HCT AD2
	HCN AD1	HCN AD2	HCN AD1	HCN AD2	HCN AD1	HCN AD2
14 days	OPC AD1	OPC AD2	OPC AD1	OPC AD2	OPC AD1	OPC AD2
	HCT AD1	HCT AD2	HCT AD1	HCT AD2	HCT AD1	HCT AD2
	HCN AD1	HCN AD2	HCN AD1	HCN AD2	HCN AD1	HCN AD2

In this case, 5(five) samples were made for each type of concrete mixture of beam samples, therefore 270 concrete beam samples were cast. The concrete mix proportioning used to characterize the behavior of fresh and hardened concrete is labeled as described in Table 7 and the concrete mix proportioning design can be seen in Table 8. As can be seen in Table 8, in the experimental optimization processes, the volumes of cement content, and coarse and fine aggregates were kept unchanged. The water content for 1 m^3 of concrete is changed, depending on the water-to-cement ratio of the concrete mixture. The dosage of admixtures for each type of concrete mix design is experimentally optimized to achieve key performance indicators in fresh concrete workability, as well as the flexural strength of hardened concrete of the high early strength concrete described previously.

Table 8. Typically concrete mixture (m^3 of concrete).

Type of Material	Source	Unit	Beam Sample		
			Cement = 500 kg/m^3 ; w/c = 0.32		
			HCT AD1	HCN AD1	HCT AD1
Cement 1	OPC	kg	0	0	0
Cement 2	HCN	kg	0	500	0
Cement 3	HCT	kg	500	0	500
Gravel	Split 10 - 20 mm Maloko	kg	1120	1120	1120
Sand 1	Silika Belitung	kg	517	517	517
Sand 2	Wash M-Sand Maloko	kg	92	92	92
Water		kg	160	160	160
AD 1	Type F	mL	1.725	1.725	1.725
	Type B	mL	5.357	5.071	5.100
AD 2	Type G	mL	0	0	0

The mixing of each type of concrete mixture was carried out based on the type of concrete beam samples described previously and the addition of admixture dosages follows the concrete mixing processes carried out. In the case of admixture-1 labeled as AD1, where the retarder and the superplasticizer are separate chemicals, 100% of the retarder is dissolved in the fresh dirt-free water and 80% of the superplasticizers are poured into the concrete mixture and mixed for 8 minutes. If the targeted first slump value was not reached, then the rest of 20% of the superplasticizer was poured into the concrete mixture and it was mixed for 2 minutes. If the targeted first slump value was still not yet reached, then a small amount of superplasticizer of 10% of the initial dosage was added and it was mixed for about 2 minutes. And this was repeatedly performed until the first slump value was reached. Whilst, for the admixture-2 labeled as AD2, where the retarder and superplasticizer are formulated as a combination of the two, 80% of the admixtures is poured into the concrete mixture and is mixed for 8 minutes. If the targeted first slump value was not reached, then a similar procedure was carried out as the case for the admixture-1. The determination of admixture dosages used in concrete mixtures was carried out by performing dosage experimental optimization in the mortar mixture consisting of fine aggregates, cement, and water, in which a low water-to-cement (w/c) ratio was used[38,39]. A small percentage of admixtures by weight of cement (bwc) was added to the cement mortar mixture. For the case of the AD1 admixture, based on the dosage optimization experimentally in cement mortar with a w/c ratio of 0.30, the dosage of retarder was found in the optimized value of 0.35% bwc and the superplasticizer was taken at 0.80% bwc. Whilst for the AD2 admixture where the retarder and the superplasticizer chemicals are produced in a combination of both chemicals, the initial dosage of AD2 admixture was taken at 0.80% bwc.

2.1.3 Tests of fresh and hardened concrete tests Test of the slump of fresh concrete

The behavior of fresh concrete is characterized by the slump test, slump lost in 2 hours, and initial setting time of various concrete mixtures designed in this work. The slump tests of fresh concrete were carried out based on Indonesian Standard, SNI 1972: 2008, where the slump truncated cone geometry used herein is depicted in Fig. 6, which is Abram's cone.

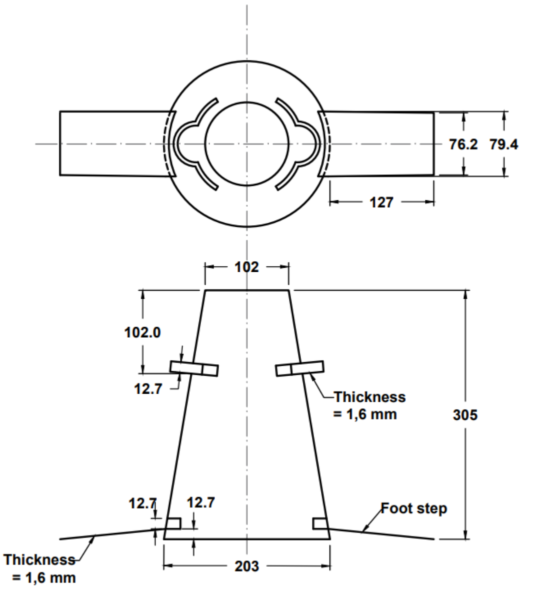


Fig. 6: Slump Test Mold (Abram's Cone).

Typically, the slump test measurement can be seen in Fig. 7.

(a) Normal flow of concrete (b) High flow of concrete.
Fig. 7: Slump Tests of fresh concrete.

In the case of the normal flow of fresh concrete the height of the slump is measured as seen in Fig. 7(a), whereas, for the high flow of concrete, the diameter of a slump is measured as seen in Fig. 7(b). The slump value of freshly mixed concrete is measured at t=0.0 as an initial time, t= 30 minutes, t= 60 minutes, t= 90 minutes, and t= 120 minutes, sequentially.

2.1.3.1 Initial Setting Time of Fresh Concrete

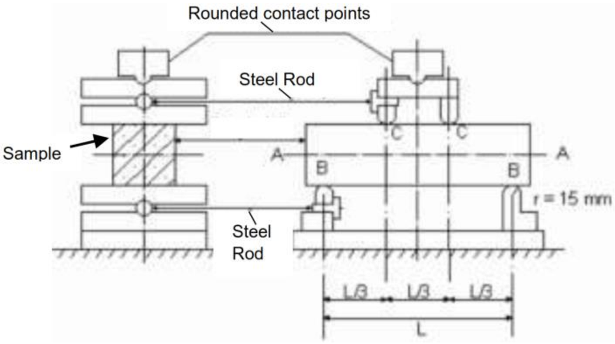
The initial setting time of fresh concrete mixture is measured using ASTM C403[14)], in which the test method employs the penetration resistance measurements on mortar sieved from the concrete mixture.

(a) Preparation of mortar sieved from concrete mixtures.

(b) Apparatus for setting time measurement.
Fig. 8: Sample preparation and apparatus for the initial setting time measurement.

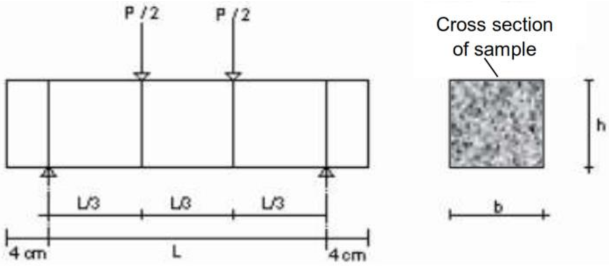
2.1.3.2 Flexural test of hardened concrete

The beam sample with a geometry of 15.0 x15.0 x 60.0 cm^3, which conforms to Indonesian Standard, SNI 4431: 2011- Concrete flexural test[13)]. The type of concrete beam samples characterized by the type of cement, the value water-to-cement ratio (w/c), and the type of admixture used can be seen in Table 7. The flexural strength (FS) of concrete is measured in beam samples at the age of 1 day, 3 days, and 14 days. The sample coding, incorporating a type of cement, type of admixture, water-to-cement ratio w/c, and age of hardened concrete can be seen in Table 7. The configuration of the flexural test based on Indonesian Standard, SNI 4431: 2011- Method of flexural test for normal concrete under two-point load[13)] and the experimental setup, can be seen in Fig. 9. In this case, the loading rate applied to the beam sample is 8 kg/cm^2 per minute, which complies with Indonesian Standard, SNI 4431: 2011.



(a) Schematic Jigs and Fixtures of Flexural Test[13)].

(b) Four-point flexural test configuration.

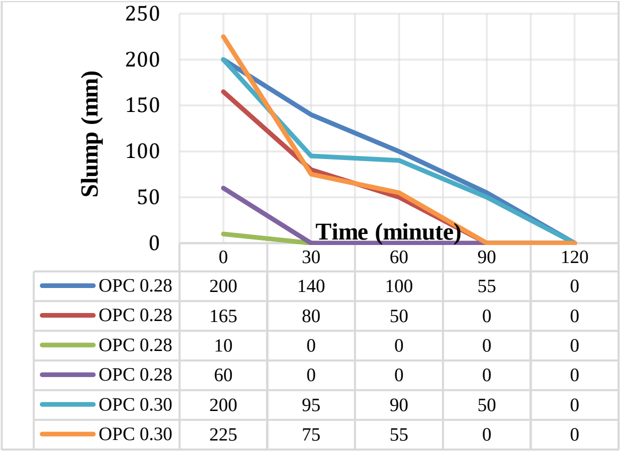


(c) Loading on beam samples of 15.0 x15.0 x 60.0 cm[13)].
Fig. 9: Flexural strength test setup of beam sample.

The pure bending condition with a 4-point load test could be obtained in the third middle span of the sample beam.

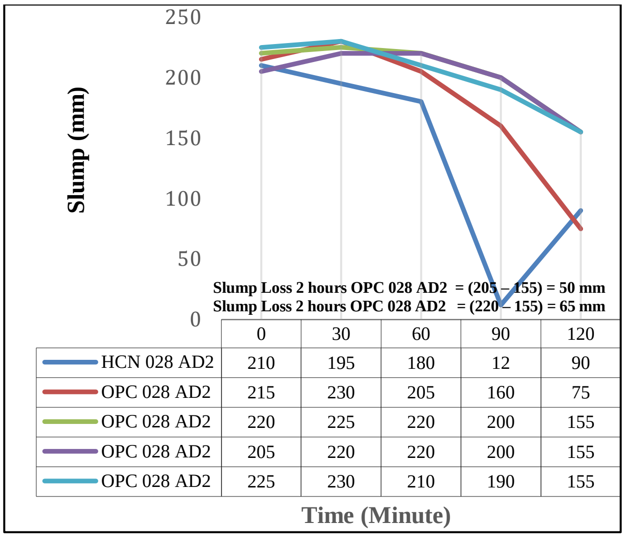
3. Results

The slump test results for various types of fresh concrete mixtures can be seen in Fig. 10 (a), (b), (c), (d).



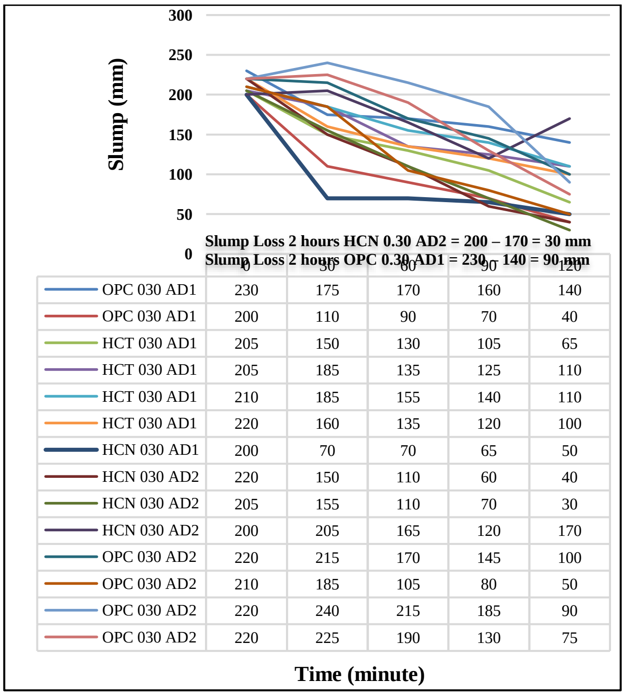
	0	30	60	90	120
OPC 0.28	200	140	100	55	0
OPC 0.28	165	80	50	0	0
OPC 0.28	10	0	0	0	0
OPC 0.28	60	0	0	0	0
OPC 0.30	200	95	90	50	0
OPC 0.30	225	75	55	0	0

(a) Slump Values for OPC concrete mixture



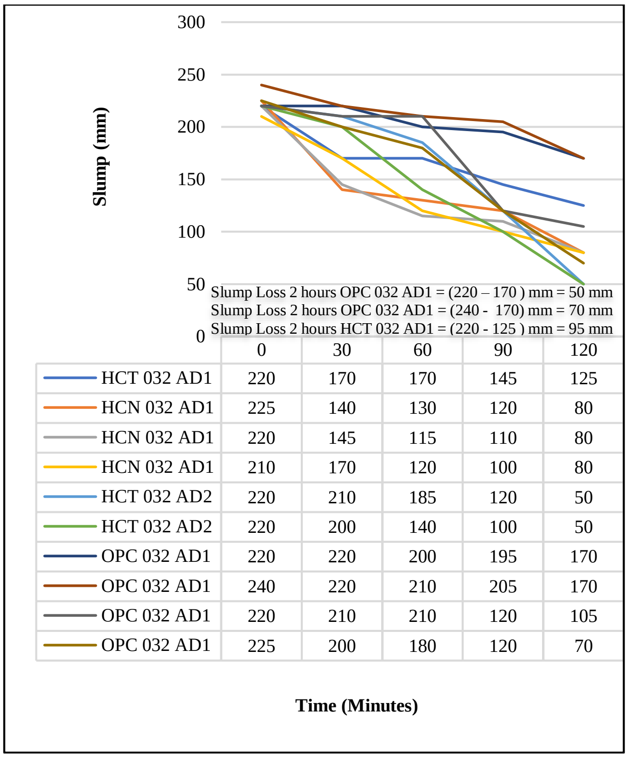
	0	30	60	90	120
HCN 028 AD2	210	195	180	12	90
OPC 028 AD2	215	230	205	160	75
OPC 028 AD2	220	225	220	200	155
OPC 028 AD2	205	220	220	200	155
OPC 028 AD2	225	230	210	190	155

(b) Slump Values for OPC and HCN concrete mixture.



	0	30	60	90	120
OPC 030 AD1	230	175	170	160	140
OPC 030 AD1	200	110	90	70	40
HCT 030 AD1	205	150	130	105	65
HCT 030 AD1	205	185	135	125	110
HCT 030 AD1	210	185	155	140	110
HCT 030 AD1	220	160	135	120	100
HCN 030 AD1	200	70	70	65	50
HCN 030 AD2	220	150	110	60	40
HCN 030 AD2	205	155	110	70	30
HCN 030 AD2	200	205	165	120	170
OPC 030 AD2	220	215	170	145	100
OPC 030 AD2	210	185	105	80	50
OPC 030 AD2	220	240	215	185	90
OPC 030 AD2	220	225	190	130	75

(c) Slump Values for OPC, HCN, and HCT concrete mixture with admixtures AD1 and AD2.

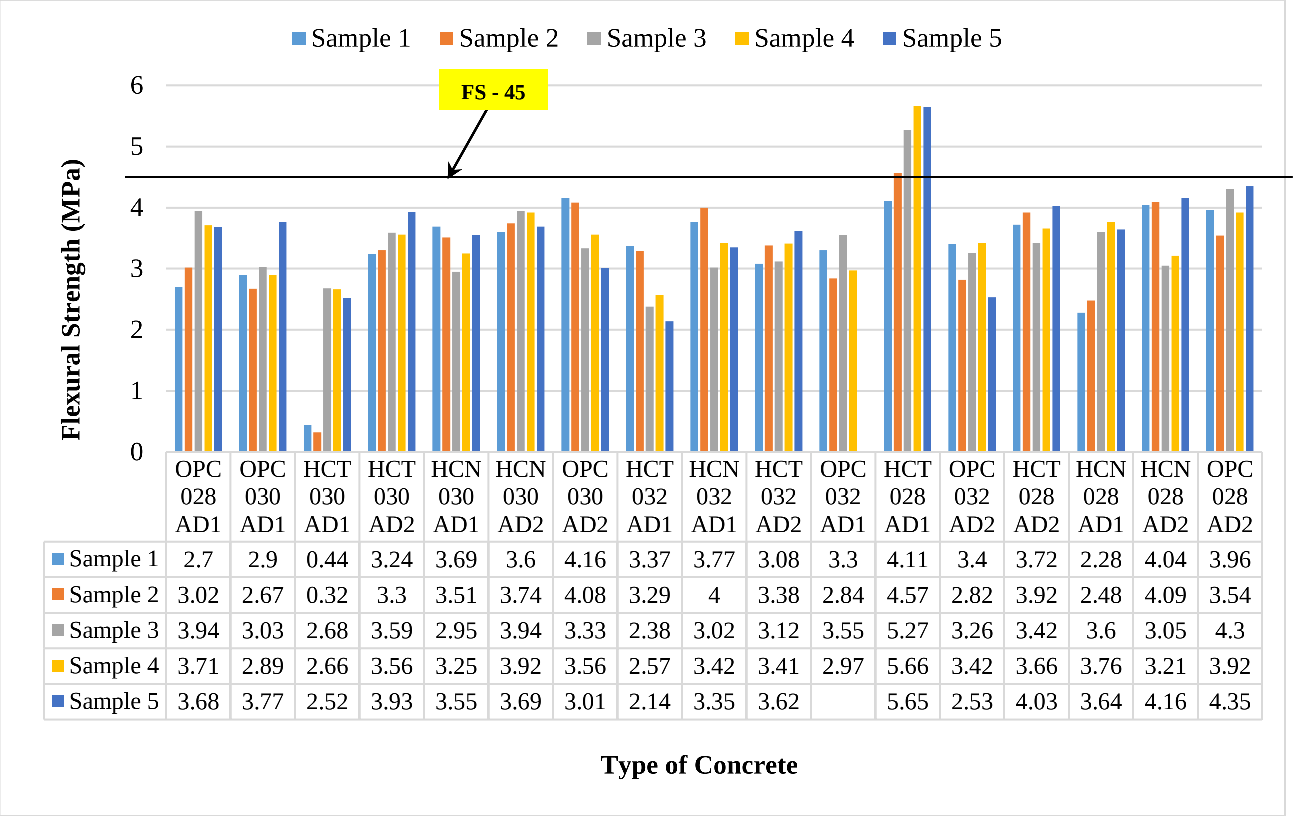


	0	30	60	90	120
HCT 032 AD1	220	170	170	145	125
HCN 032 AD1	225	140	130	120	80
HCN 032 AD1	220	145	115	110	80
HCN 032 AD1	210	170	120	100	80
HCT 032 AD2	220	210	185	120	50
HCT 032 AD2	220	200	140	100	50
OPC 032 AD1	220	220	200	195	170
OPC 032 AD1	240	220	210	205	170
OPC 032 AD1	220	210	210	120	105
OPC 032 AD1	225	200	180	120	70

(d) Slump values for OPC, HCN, and HCT concrete mixture with w/c = 0.32, admixtures AD1 and AD2.

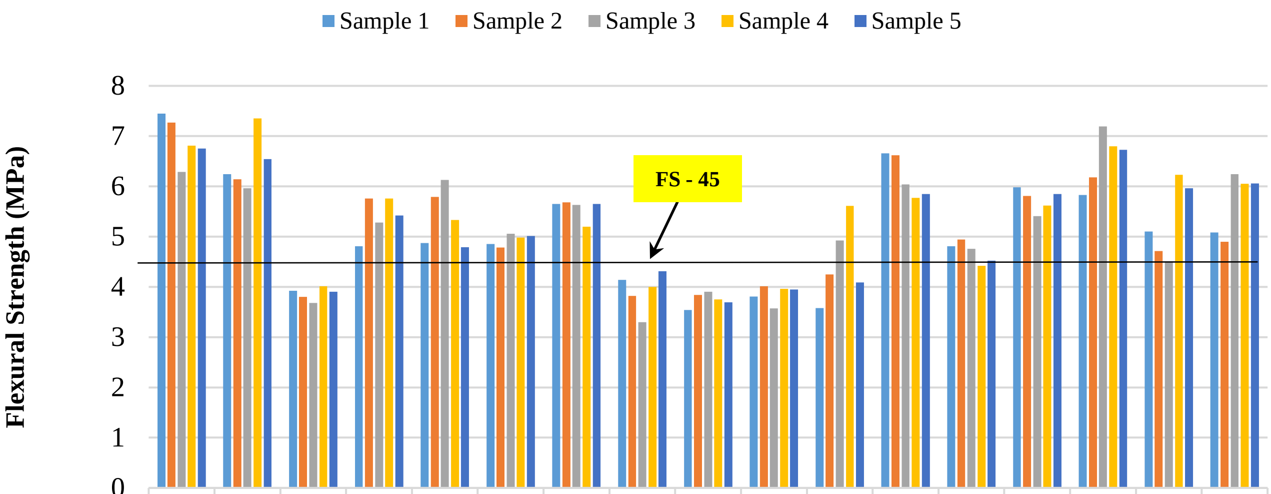
Fig. 10: Slump values for various concrete mix design.

The results of the flexural strength of the concrete mixture for various types of concrete beam samples at the age of 1 day, 3 days, and 14 days of age can be seen in Fig. 11, Fig. 12, and Fig. 13 respectively. Initially, concrete goes through a plastic or fluid state, allowing it to be shaped and molded. As hydration progresses, the concrete undergoes a setting process, during which it gradually transforms from a plastic state to a rigid one. The concrete continues to gain strength and harden over an extended period as hydration reactions continue. For each type of concrete mixture, 5 (five) samples were made to see the consistency of the flexural strength results obtained. The flexural strength of 3 days of age of concrete as depicted in Fig. 12 is obtained by averaging the results from 5 (five) samples tested. As can be seen in Fig. 11, Fig. 12, and Fig. 13, in general, the development of flexural strength of each beam sample is in increasing order from the flexural strength of 1 day to 3 days of age samples. Furthermore, the flexural strength of beam samples increasingly developed to a much higher flexural strength as the age-progressed to 14 days. This attainment of flexural strength of 4.50 MPa within the 3 days may be classified as a high early strength concrete (HESC). Based on the Research Centre for Roads and Bridges, the Ministry of Public Work and Housing, the requirements for concrete rigid pavements in road infrastructure construction works and development require a flexural strength of 4.50 MPa within 28 days of the age of concrete pavement for its production controls$^{16,36)}$. In this work, the HESC target of flexural strength of 4.50 MPa reached within 3 days of age is attempted. As depicted in Figure 11, for the 1 day of age of concrete, the FS 45 could only be obtained for the HCT-based concrete with the average values of 5.10 MPa., employing AD1 admixtures. As the age of concrete progresses, for the 3 days of age, there are 12 out of 17 types of concrete that could achieve FS 45 within 3 days of age, as can be seen in Fig. 12. However, all concrete mixtures with w/c ratio = 0.32 failed to reach FS 45 in 3 days of age, except for the OPC-based concrete mixture using AD2 admixture where flexural strength of 4.69 MPa is still able to be attained. Since a w/c ratio of 0.32 is the highest value of the w/c ratio in this work, it is expected that the flexural strength will be the lowest. This condition implies that to have a high early strength concrete with w/c ratio = 0.32 and cement content of 500 kg per m^3 is difficult to achieve.



	OPC 028 AD1	OPC 030 AD1	HCT 030 AD1	HCT 030 AD2	HCN 030 AD1	HCN 030 AD2	OPC 030 AD2	HCT 032 AD1	HCN 032 AD1	HCT 032 AD2	OPC 032 AD1	HCT 028 AD1	OPC 032 AD2	HCT 028 AD2	HCN 028 AD1	HCN 028 AD2	OPC 028 AD2
Sample 1	2.7	2.9	0.44	3.24	3.69	3.6	4.16	3.37	3.77	3.08	3.3	4.11	3.4	3.72	2.28	4.04	3.96
Sample 2	3.02	2.67	0.32	3.3	3.51	3.74	4.08	3.29	4	3.38	2.84	4.57	2.82	3.92	2.48	4.09	3.54
Sample 3	3.94	3.03	2.68	3.59	2.95	3.94	3.33	2.38	3.02	3.12	3.55	5.27	3.26	3.42	3.6	3.05	4.3
Sample 4	3.71	2.89	2.66	3.56	3.25	3.92	3.56	2.57	3.42	3.41	2.97	5.66	3.42	3.66	3.76	3.21	3.92
Sample 5	3.68	3.77	2.52	3.93	3.55	3.69	3.01	2.14	3.35	3.62		5.65	2.53	4.03	3.64	4.16	4.35

Fig. 11: Flexural strength of various concrete mixtures at 1 day of age.

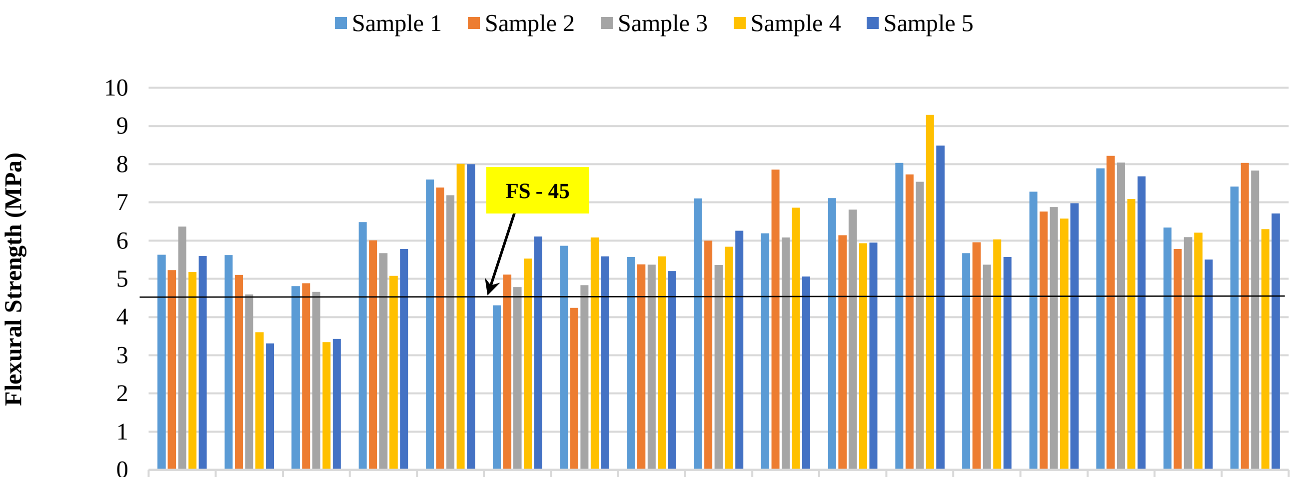


	OPC 0,28 AD1	OPC 0,30 AD1	HCT 0,30 AD1	HCT 0,30 AD2	HCN 0,30 AD1	HCN 030 AD2	OPC 030 AD2	HCT 032 AD1	HCN 032 AD1	HCT 032 AD2	OPC 032 AD1	HCT 028 AD1	OPC 032 AD2	HCT 028 AD2	HCN 028 AD1	HCN 028 AD2	OPC 028 AD2
Sample 1	7.45	6.24	3.92	4.81	4.87	4.85	5.65	4.14	3.54	3.81	3.58	6.66	4.81	5.98	5.83	5.1	5.08
Sample 2	7.27	6.14	3.80	5.76	5.79	4.78	5.68	3.82	3.84	4.01	4.25	6.62	4.94	5.81	6.18	4.71	4.9
Sample 3	6.29	5.96	3.68	5.28	6.13	5.06	5.63	3.3	3.9	3.57	4.92	6.04	4.76	5.41	7.19	4.51	6.24
Sample 4	6.81	7.35	4.01	5.76	5.33	4.98	5.2	4	3.75	3.96	5.61	5.77	4.42	5.62	6.8	6.23	6.05
Sample 5	6.75	6.54	3.90	5.42	4.79	5.01	5.65	4.31	3.69	3.95	4.09	5.85	4.52	5.85	6.73	5.96	6.06

Average (MPa.)	6,91	6,45	3,86	5,41	5,38	4,94	5,56	3,91	3,74	3,86	4,49	6,19	4,69	5,73	6,55	5,30	5,67
Standard Dev.	0,46	0,55	0,13	0,39	0,58	0,12	0,20	0,39	0,14	0,01	1,07	0,06	0,07	0,16	0,05	0,19	0,01

Type of Concrete

Fig. 12: Flexural strength of various concrete mixtures at 3 days of age.



	OPC 0,28 AD1	OPC 0,30 AD1	HCT 0,30 AD1	HCT 0,30 AD2	HCN 0,30 AD1	HCN 0,30 AD2	OPC 0,30 AD2	HCT 0,32 AD1	HCN 0,32 AD1	HCT 0,32 AD2	OPC 0,32 AD1	HCT 0,28 AD1	OPC 0,32 AD2	HCT 0,28 AD2	HCN 0,28 AD1	HCN 0,28 AD2	OPC 0,28 AD2
Sample 1	5.63	5.62	4.81	6.48	7.60	4.31	5.86	5.57	7.10	6.19	7.11	8.03	5.67	7.28	7.89	6.34	7.41
Sample 2	5.23	5.10	4.88	6.01	7.39	5.11	4.24	5.38	6.00	7.86	6.14	7.73	5.96	6.76	8.22	5.78	8.03
Sample 3	6.37	4.59	4.66	5.67	7.19	4.78	4.83	5.37	5.36	6.08	6.81	7.54	5.37	6.88	8.04	6.09	7.83
Sample 4	5.18	3.60	3.34	5.08	8.01	5.53	6.08	5.59	5.84	6.86	5.93	9.29	6.03	6.58	7.09	6.21	6.30
Sample 5	5.60	3.31	3.43	5.78	8.00	6.11	5.59	5.20	6.26	5.06	5.95	8.49	5.57	6.98	7.68	5.50	6.71

Type of Concrete

Fig. 13: Flexural strength of various concrete mixtures at 14 days of age.

For the 14 days of age, all of the flexural strength of concrete increased quite significantly. All concrete mixtures could reach FS 45 except for OPC- and HCT-based concrete with a w/c ratio of 0.30 utilizing AD1 admixture. The condition of lower w/c ratio in concrete typically results in higher flexural strength due to improved overall durability and reduced porosity. With less water, the concrete mix has a lower moisture content, leading to a more tightly packed structure. This results in fewer voids and a stronger interlocking matrix, enhancing the material's ability to withstand bending forces, such as those experienced in flexural situations. Additionally, lower water content contributes to decreased shrinkage and improved resistance to cracking, further enhancing flexural strength.

Admixture plays a crucial role in developing high early strength concrete (HESC) by enhancing various properties of the concrete mixture, either in fresh states or in hardened states. In this work, retarding admixtures can also be beneficial in HESC formulations. While seemingly counterintuitive, they slow down the setting time, providing more time for concrete placement and consolidation. This extended workability can be advantageous in complex construction scenarios. While superplasticizer admixtures improve workability without increasing water content. Superplasticizers disperse cement particles more effectively than water reducers, allowing for a highly fluid mix. This is valuable in high-strength concrete or when achieving intricate shapes without compromising strength. The results of workability performance of various types of fresh concrete, i.e. initial slump values and slump histories every 30 minutes within 120 minutes, slump loss within 2 hours, initial setting time of fresh concrete mortar for the HCN, HCT, and OPC – based concrete can be seen in Table 9, Table 10 and Table 11, respectively.

Table 9. Flexural Strength and Workability Performances of HCN Concrete.

No.	Type of Concrete	w/c ratio	Flexural Strength – 3 days of age (MPa.)	Slump (mm) / Slump Loss in 2 hours (mm) / Initial Setting Time (hours)					Qualification For HESC
1	HCN 030 AD1	0,30	5,38	Initial Slump	165	200	145	120	Qualified
				Slump 30"	125	70	60	65	
				Slump 60"	70	70	45	60	
				Slump 90"	55	65	-	25	
				Slump 120"	-	50	-	-	
				Slump Loss	N/A	150	N/A	N/A	
				Initial Set Time (hour)	13.8	11.7	11.3	9.5	
2	HCN 030 AD2	0,30	4,94	Initial Slump	200	220	205	200	Qualified
				Slump 30"	130	150	155	205	
				Slump 60"	90	110	110	165	
				Slump 90"	45	60	70	120	
				Slump 120"	-	40	30	170	
				Slump Loss	N/A	180	175	30	
				Initial Set Time (hour)	12.2	14.9	11.9	14.3	
3	HCN 028 AD1	0,28	6,55	Initial Slump	225	220	205	210	Not Qualified
				Slump 30"	180	190	110	170	
				Slump 60"	155	150	40	60	
				Slump 90"	35	50	-	-	
				Slump 120"	-	-	-	-	
				Slump Loss	N/A	N/A	N/A	N/A	
				Initial Setting Time (jam)	17.8	18.1	15.1	8.3	
4	HCN 028 AD2	0,28	5,30	Initial Slump	220	205	210	200	Qualified
				Slump 30"	170	150	195	135	
				Slump 60"	115	70	180	85	
				Slump 90"	30	40	12	40	
				Slump 120"	-	-	90	-	
				Slump Loss	N/A	N/A	120	N/A	
				Initial Setting Time (hour)	6.7	6.5	7.6	6.6	

Table 10. Flexural Strength and Workability Performance of HCT Concretes.

No.	Type of Concrete	w/c ratio	Flexural Strength – 3 days of age (MPa.)	Slump (mm) / Slump Loss in 2 hours (mm) /Initial Setting Time (hours)					Qualification for HESC
1	HCT 030 AD2	0,30	5,41	Initial Slump	200	205	210	220	Not Qualified
				Slump 30"	40	145	50	75	
				Slump 60"	-	85	-	35	
				Slump 90"	-	55	-	-	
				Slump 120"	-	-	-	-	
				Slump Loss	N/A	N/A	N/A	N/A	
				Initial Setting Time (jam)	9.7	9.5	10.5	11.2	
2	HCT 028 AD1	0,28	6,19	Initial Slump	230	230	200	210	Qualified
				Slump 30"	230	210	50	0	
				Slump 60"	210	170	-	-	
				Slump 90"	185	140	-	-	
				Slump 120"	65	25	-	-	
				Slump Loss	165	205	N/A	N/A	
				Initial Setting Time (jam)	7.5	9.4	14.5	13.7	
3	HCT 028 AD2	0,28	5,73	Initial Slump	260	260	250	220	Not Qualified
				Slump 30"	245	230	145	95	
				Slump 60"	55	60	30	15	
				Slump 90"	-	-	-	-	
				Slump 120"	-	-	-	-	
				Slump Loss	N/A	N/A	N/A	N/A	
				Initial Setting Time (jam)	7.5	8.3	7.0	5.3	

Table 11. Flexural Strength and Workability Performances of OPC Concretes.

No.	Type of Concrete	w/c ratio	Flexural Strength – 3 days of age (MPa.)	Slump (mm) / Slump Loss in 2 hours (mm) /Initial Setting Time (hours)					Qualification for HESC
1	OPC 028 AD1	0,28	6,91	Initial Slump	200	165	10	60	Not Qualified
				Slump 30"	140	80	-	-	
				Slump 60"	100	50	-	-	
				Slump 90"	55	-	-	-	
				Slump 120"	-	-	-	-	
				Slump Loss (mm)	N/A	N/A	N/A	N/A	
				Initial Setting Time (hour)	6.8	8.5	N/A	N/A	
2	OPC 030 AD1	0,30	6,45	Initial Slump	200	230	200	225	Qualified
				Slump 30"	95	175	110	75	
				Slump 60"	90	170	90	55	
				Slump 90"	50	160	70	-	
				Slump 120"	-	140	40	-	
				Slump Loss (mm)	N/A	90	160	N/A	
				Initial Setting Time (hour)	8.1	13.6	9.8	11.8	
3	OPC 030 AD2	0,30	5,56	Initial Slump	200	230	200	225	Qualified
				Slump 30"	95	175	110	75	
				Slump 60"	90	170	90	55	
				Slump 90"	50	160	70	-	
				Slump 120"	-	140	40	-	
				Slump Loss	N/A	90	160	N/A	
				Initial Setting Time (hour)	8.1	13.6	9.75	11.8	
4	OPC 032 AD2	0,32	4,69	Initial Slump	225	210	220	225	Qualified
				Slump 30"	240	140	220	230	
				Slump 60"	200	110	210	-	
				Slump 90"	95	40	19	-	
				Slump 120"	55	-	115	220	
				Slump Loss	170	N/A	105	N/A	
				Initial Setting Time (jam)	15.3	15.6	13.6	13.2	
5	OPC 028 AD2	0,28	5,67	Initial Slump	215	220	205	225	Qualified Rank 1
				Slump 30"	230	225	220	230	
				Slump 60"	205	220	220	210	

				Slump 90"	160	200	200	190	
				Slump 120"	75	155	155	155	
				Slump Loss	140	65	50	70	
				Initial Setting Time (jam)	12.2	14.9	11.9	14.3	

The initial setting times are obtained from the setting time curves measured in this work, typically for HCN 0.28 AD1 can be seen in Fig. 14.

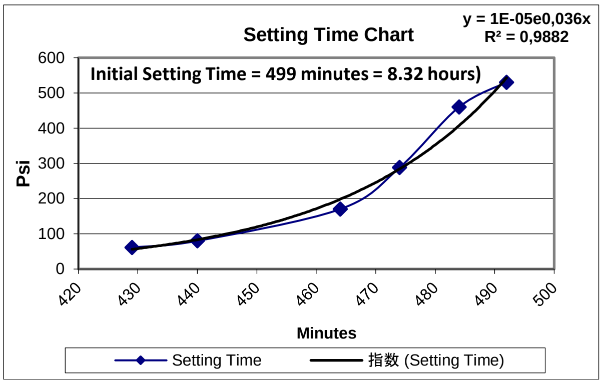


Fig. 14: Typically Setting Time Result Plotting.

The initial setting times for various fresh concrete mortar can be seen in Fig. 14. The initial setting time of concrete mortar is the time that takes for the mixture to stiffen and resist penetration. It is typically determined by conducting the Vicat test, where a standardized needle is used to penetrate the mortar at regular intervals until it can no longer penetrate. To perform the test, a Vicat apparatus is used to measure the penetration resistance of the mortar sample. The initial setting time is the point at which the needle barely makes an impression on the surface. This test helps ensure that the mortar has gained enough strength to support its weight and resist deformation. The initial setting time of concrete or mortar can be influenced by several factors, including:

(a) Mix Proportions: the ratio of cement, water, aggregates, and any additives in the mix can affect the setting time. Different proportions can lead to variations in the chemical reactions responsible for the setting.

(b) Cement Type: various types of cement have different setting characteristics. For example, rapid-setting cement will set faster than ordinary Portland cement.

(c) Temperature: The setting time is sensitive to temperature. Higher temperatures generally accelerate the setting process, while lower temperatures can slow it down.

(d) Humidity: the moisture content in the environment can impact the setting time. Higher humidity levels may slow down the setting process.

(e) Admixtures: the use of chemical admixtures, such as superplasticizers or retarders, can be employed to control or modify the setting time based on project requirements.

(f) Curing Conditions: how the concrete mortar is cured after placement can influence the setting time. Proper curing is essential for achieving the desired strength and durability.

(g) Agitation and Placement: the way the mix is handled, including mixing and placing techniques, can affect the setting time.

(h) Size and Shape of Aggregates: the characteristics of the aggregates used in the mix can impact the setting time. Finer aggregates may lead to faster settings.

It is of paramount importance to consider these factors in the context of specific project requirements and conditions to ensure the concrete mortar sets appropriately for the intended application. In this work, the variation of the initial setting time of various concrete mortar can be seen in Fig. 15. The highest initial setting time was found at 18.1 hours of HCN 0.28 AD1 and the initial setting time of 5.3 hours of HCT 0.28 AD2 was the lowest one. None of the concrete mixtures happened to have slow set conditions and all of the beam samples can be tested in their flexure strength at the age of one day (24 hours). It is observed at three days of age, see Fig. 12, that the average flexural strength of HCN 0.28 AD1 was 6.55 MPa exceeding the target of FS 45 that 4.50 MPa. Similarly, in the case of HCT 0.28 AD2 where the lowest initial setting time was in this group of samples, the average flexural strength was found at 5.73 MPa surpassing the FS 45 at three days of age. The detailed experimental data which explains the results consisting of initial setting time measurements for various types of concrete mixtures of HCN, HCT, and OPC, can be seen in Table 9, Table 10, and Table 11 respectively.

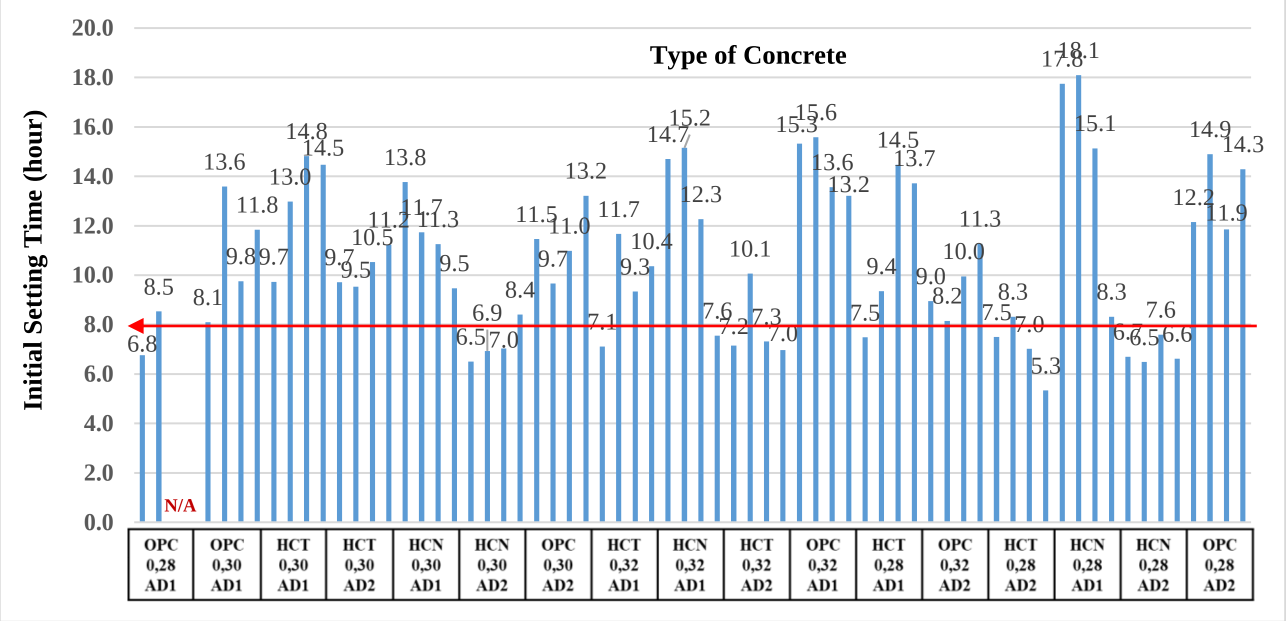
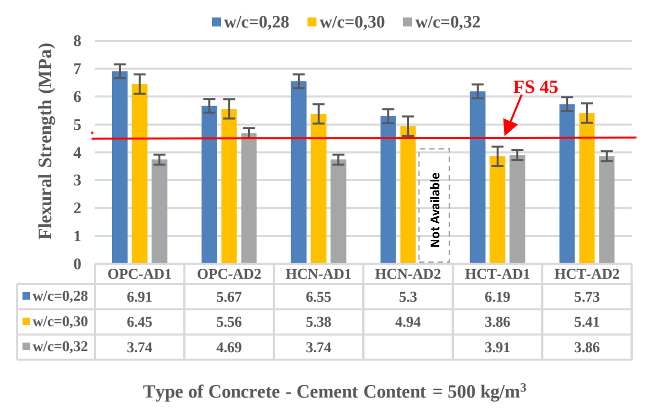


Fig. 15: Initial Setting Time for various types of concrete.

The type of concrete mixtures that could satisfy the high early strength concrete criteria of flexural strength of 4.5 MPa. or 45 kg/cm^2 within 3 (three) days of age (termed as FS 45) can be seen in Fig. 16, as the following.



	OPC-AD1	OPC-AD2	HCN-AD1	HCN-AD2	HCT-AD1	HCT-AD2
w/c=0,28	6.91	5.67	6.55	5.3	6.19	5.73
w/c=0,30	6.45	5.56	5.38	4.94	3.86	5.41
w/c=0,32	3.74	4.69	3.74		3.91	3.86

Fig. 16: Flexural strength of concrete at 3 days of age versus w/c ratio.

4. Discussions

The water-to-cement ratio is a critical factor in the performance of concrete, influencing both its strength and durability. In the context of high early-strength concrete formulations, the relationship between water-to-cement ratio and flexural strength is significant. In this work, the best concrete mixture performance is selected using the key performance indicators of workability and flexural strength determined previously as target values. Not all of the workability performance indicators are satisfied, such as slump losses in 2 hours, and historical slump values of 30, 60, 90, and 120 minutes, therefore as in the absence of these slump workability indicators, the related concrete mixtures are not qualified to be selected as HESC. Also, in the case of the initial setting time of fresh concrete mortar, the criteria of targeted values of 8.0 hours are not entirely satisfied. As long as the slow set conditions are up to 20 hours do not occur, the related concrete mixtures could be still taken into account as qualified concrete mixtures to be tested its flexural strength. As depicted in Tables 9, 10, and 11, it is found that the concrete mixtures passed the key performance indicators, including the flexural strength of FS 45 at 3 days of age, as stated previously could be seen in the following Table 12.

Table 12. Concrete Mixtures Qualified for HESC.

No	**Type of concrete**	**FS 45 at 3 days of age (MPa.)**	**HESC Mixture Qualified**
1.	OPC	6.45	OPC 030 AD1
		5.67	OPC 028 AD2
		4.69	OPC 032 AD2
2.	Hydraulic Cement - HCN	5.30	HCN 028 AD2
		4.94	HCN 030 AD2
3.	Hydraulic Cement - HCT	6.19	HCT 028 AD1

As can be seen in Fig. 16, it is found that the flexural strength of three days of the age of all types of the concrete mixture has a relationship: the lower the water-to-cement ratio the higher the flexural strength, for the certain cement content used. In this work, all types of concrete use a cement content of 500 kg per m^3 volume of concrete. For all types of concrete with a w/c ratio of 0.28 and within three days of age, both OPC-based- and HC-based concrete could convincingly reach the flexural strength key performance indicator of 4.5 MPa. or 45 kg/cm^2 within three days of age (i.e. it is termed as FS 45 in Fig. 16. In the case of a w/c ratio of 0.30, only the hydraulic cement of HCT-based concrete with the use of AD1 admixture could not reach the FS 45 key performance indicator, whilst the others could again convincingly reach FS 45 successfully. For a higher w/c ratio of 0.32, the only type of concrete that could reach FS 45 within three days of age comes from the OPC-based concrete utilizing AD2 admixture. Therefore, in the case of high early strength concrete (HESC) mix design, for all types of hydraulic cement-based concrete utilizing the w/c ratio of 0.28, cement content of 500 kg/m^3 and optimized dosages of admixtures could substitute the use of similar mix formulation of OPC-based concrete which has more CO_2e compared to the HC-based concrete. In the context of HESC with 3 days of age reaching FS 45, as seen in Fig. 17, there is a trade-off between the flexural Strength vs. CO_2e. As depicted in Fig. 17, the trade-off between the flexural strength and CO_2e, for w/c ratios of 0.28 and 0.30, there are degradation in the flexural strength of 5.21% and 16.59% respectively, while it is still maintaining the FS 45. Switching from OPC-based to HC-based concrete, results in a decrease in CO_2e from 814 kg to 703 per ton of cement production of as much as 13.64%. Therefore, OPC is known for its high clinker content, contributing significantly to CO_2e during production. Whilst, hydraulic cement (HC) with a lower clinker factor, such as those incorporating supplementary cementitious materials (SCMs) like fly ash or slag, generally could result in reduced CO_2e17,18,33).

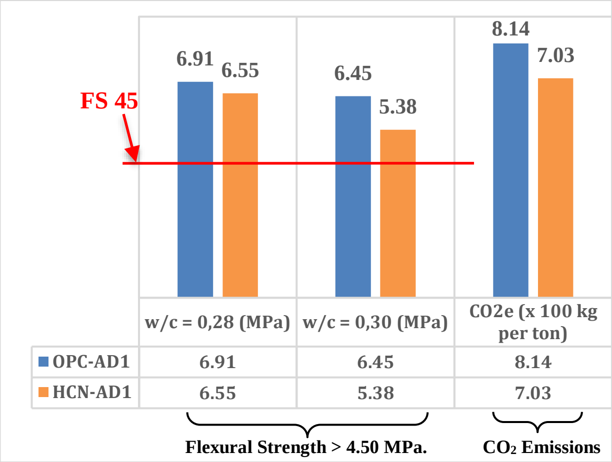


Fig. 17: The trade-off between Flexural Strength vs. CO_2e.

Choosing hydraulic cement with a lower clinker factor provides a clear trade-off by addressing environmental concerns related to CO_2e while maintaining a balance in flexural strength. The trade-off may be acceptable in many applications, especially where environmental considerations are a priority, and slight variations in flexural strength are permissible. Lowering the clinker factor aligns with sustainability goals, as it directly reduces the carbon footprint associated with concrete production.

The relationship between initial setting time and flexural strength in concrete is influenced by the hydration process. Initial setting time is the time it takes for concrete to stiffen and resist deformation, while flexural strength measures its ability to withstand bending stresses. During the initial setting time, the cement in concrete undergoes hydration, a chemical reaction where water reacts with the cement particles, forming a solid matrix. This matrix contributes to the overall strength of the concrete.

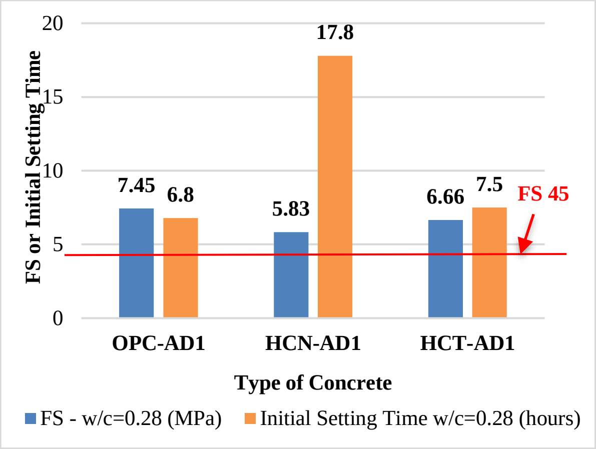


Fig. 18: Flexural Strength vs. Initial Set. Time for w/c ratio of 0.28.

The relationship between initial setting time and flexural strength for a w/c ratio of 0.28 and 0.30 can be seen in Fig. 18 and Fig. 19 respectively. The different relationships for different w/c ratios are noticeable. In this context, the types of concrete mixtures with AD1 admixture are considered. The concrete mixtures used in the flexural strength tests are taken from the same concrete mixture used in the measurement of initial setting time, i.e. a concrete mixture of OPC-AD1, HCN-AD1, and HCT-AD1, with w/c ratios of 0.28 and 0.30 respectively.

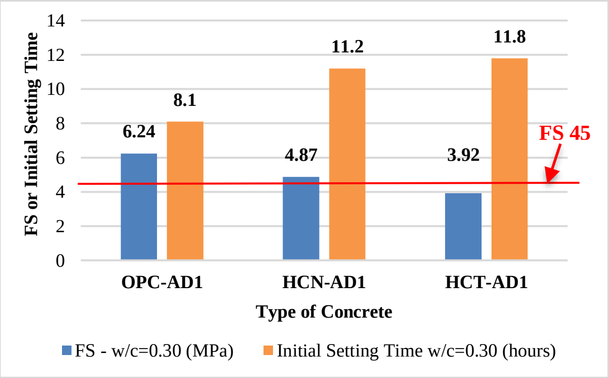


Fig. 19: Flexural Strength (FS) vs Initial Set. Time for w/c ratio of 0.30.

As can be seen in Fig. 18 and Fig. 19, it is found that the higher the initial setting time can be, the lower the flexural strength that can be obtained. In the case of normal concrete, the mechanism at play involves the development of the cementitious gel structure during hydration. If the concrete sets too quickly, the gel may not have sufficient time to form a strong network, potentially leading to reduced flexural strength. Conversely, excessively delayed setting times may impact the overall strength development. The formation of the cementitious gel (C-S-H gel) is critical for strength development. A longer initial setting time may allow for more extensive gel formation. The speed of the hydration reaction influences the crystalline structure of the cementitious products. A rapid setting may result in smaller crystals with less interlocking strength. The rate of setting can affect the size and distribution of pores in the concrete matrix. A prolonged setting time may contribute to a more refined and interconnected pore structure. In this work, the AD1 admixture (i.e. it consists of separate retarder and superplasticizer chemicals) was employed, therefore the use of chemical admixtures can impact setting time. Some admixtures may extend setting times while enhancing the ultimate strength by promoting better microstructure development. In high-early-strength concrete, the trade-off between achieving high early strength and compromising certain aspects of mature strength, including flexural strength, is inherent. The expedited setting time and early strength may not allow for the same level of optimal microstructure development compared to conventional concrete with longer setting times. Balancing these considerations requires careful selection of materials, admixtures, and curing practices to meet the specific performance requirements.

In Indonesia, the rapid pace of urbanization and economic growth necessitates extensive transportation infrastructure development, including roads, bridges, and airports. However, traditional concrete production is highly energy-intensive and contributes significantly to CO_2 emissions. Sustainable low-carbon HPC provides an effective solution by reducing the carbon footprint of these projects while simultaneously enhancing the longevity and overall performance of the infrastructure.

The key components of low carbon HPC include the use of supplementary cementitious materials (SCMs) like fly ash, slag, and silica fume, which partially replace Portland cement and thereby reduce CO_2 emissions. Additionally, the incorporation of recycled aggregates minimizes the need for natural resources and reduces construction waste. Advanced chemical admixtures improve the workability, strength, and durability of the concrete, allowing for a reduction in cement content and, consequently, a lower environmental impact. Furthermore, energy-efficient production methods, such as using alternative fuels in kilns and adopting energy-efficient mixing processes, contribute to the overall reduction of carbon emissions associated with HPC.

Implementing sustainable HPC offers numerous benefits, including a reduced environmental impact due to lower greenhouse gas emissions and the conservation of natural resources. Economically, there is potential for cost savings through the use of locally sourced materials and waste products. Moreover, the enhanced performance of HPC - characterized by increased durability, reduced maintenance costs, and improved resistance to environmental factors - adds significant value to transportation infrastructure.

However, the implementation of sustainable HPC is not without challenges. Higher initial costs for materials and technology can present a barrier, and the successful application of this advanced concrete requires skilled labor and expertise in new construction techniques. Additionally, there is a need for updated standards and regulations to accommodate the use of these new materials and methods. Case studies from various countries provide valuable insights into the successful application of low-carbon HPC. In Indonesia, pilot projects in major cities have integrated low-carbon HPC in bridge and road construction, demonstrating the material's durability in tropical climates. Other examples include the use of sustainable HPC in highway and bridge projects in the United States, where fly ash and slag are commonly used(59,60), and in Europe, where extensive railway networks have adopted low-carbon HPC, emphasizing recycled aggregates and energy-efficient production(61-63).

To further advance the implementation of sustainable HPC in Indonesia, several recommendations can be made. Government policies should encourage the use of sustainable materials through incentives and regulations. Investment in local research and development (R&D) is crucial to optimize low-carbon HPC for Indonesia's specific environmental and structural conditions. Public-private partnerships can play a vital role in funding and implementing sustainable infrastructure projects, and education and training programs should be developed to equip engineers and construction workers with the necessary skills to use advanced concrete technologies. The adoption of sustainable low-carbon HPC in transportation infrastructure is essential for achieving both economic development and environmental sustainability. While there are challenges, the long-term benefits of using this material make it a viable and necessary investment. By learning from global examples and tailoring solutions to local needs, Indonesia and other countries can pave the way for a greener and more resilient infrastructure future.

Based on the concrete trial mix results obtained herein and discussions previously, the future research directions may be considered as follows:

(a) Optimizing High w/c Ratio Mixtures: Investigate ways to improve the flexural strength of hydraulic cement-based concrete (HCN and HCT) with higher w/c ratios (e.g., 0.32). This may involve experimenting with different admixtures, varying curing conditions, or incorporating novel materials.

(b) Admixture Performance Analysis: Conduct a comprehensive study on the effectiveness of various admixtures (AD1, AD2, and others) in enhancing both flexural strength and workability across different concrete mixtures. This research should aim to identify the optimal admixture combinations for specific applications.

(c) Advanced Workability Metrics: Develop and validate more flexible and context-specific criteria for slump loss over time. Investigate alternative measures of workability that better predict performance in real-world conditions, potentially incorporating factors like temperature, humidity, and mixing methods.
(d) Long-Term Durability Studies: Extend the investigation to long-term performance metrics, including durability, resistance to environmental degradation, and lifecycle analysis. This would provide a comprehensive understanding of how low w/c ratio mixtures perform over decades, particularly in transportation infrastructures.
(e) Environmental Impact Assessment: Perform a detailed lifecycle assessment (LCA) comparing the environmental impacts of hydraulic cement-based concrete versus OPC-based concrete. This should include not only CO2 emissions but also factors like resource consumption, energy use, and potential for recycling.
(f) Field Trials and Large-Scale Implementation: Implement pilot projects using hydraulic cement-based concrete mixtures in real transportation infrastructure developments. Monitor and analyze their performance over time to validate laboratory findings and refine the concrete mix designs based on practical feedback.
(g) Economic Feasibility Studies: Conduct a thorough economic analysis to assess the cost implications of adopting sustainable low-carbon concrete mixtures in large-scale infrastructure projects. This should include initial costs, maintenance, and long-term savings due to enhanced durability and reduced environmental impact.

5 Conclusion and Recommendation

5.1 Conclusion

The study carried out herein found that concrete mixtures with a water-to-cement (w/c) ratio of 0.28, including OPC, HCN, and HCT with admixtures AD1 and AD2, exceeded the targeted flexural strength of 4.50 MPa (FS 45) within three days of age. Concrete mixtures with a w/c ratio of 0.30 also met this target, except for HCT with AD1. However, with a w/c ratio of 0.32, only OPC with AD2 marginally exceeded FS 45.

Regarding workability, the mixtures that met FS 45 also maintained good slump values over 120 minutes and did not set slowly. These include OPC 0.28 AD2, OPC 0.30 AD1, OPC 0.32 AD2, HCN 0.28 AD2, HCN 0.30 AD2, and HCT 0.28 AD1. The slump loss over two hours for HCN 0.30 AD2, OPC 0.28 AD1, and OPC 0.28 AD2 was higher than the strict maximum criterion of 20 mm, therefore they did not perform well overall.

Hydraulic cement-based concrete embeds less CO_2 compared to OPC-based concrete, making it a more sustainable choice for transportation infrastructure developments. Using hydraulic cement with a lower clinker factor balances environmental impact and performance, supporting sustainability while meeting project-specific requirements.

5.2 Recommendations

Based on discussions and conclusions carried out previously, the recommendations may be made as the following.

(a) Adopt Low w/c Ratio Mixtures: utilize concrete mixtures with a water-to-cement ratio (w/c) of 0.28 to achieve high flexural strength and good workability. Mixtures including OPC, HCN, and HCT with admixtures AD1 and AD2 have proven to exceed the targeted flexural strength (FS 45) within three days of age.
(b) Optimize Use of 0.30 w/c Ratio Mixtures: implement mixtures with a w/c ratio of 0.30, particularly those using OPC and HCN with AD2, as they meet the flexural strength target and maintain adequate workability. Avoid using HCT with AD1 at this ratio, as it does not meet the required strength.
(c) Select Appropriate Admixtures for Higher w/c Ratios: for mixtures with a w/c ratio of 0.32, prioritize the use of OPC with AD2, as it marginally meets the flexural strength target. Other mixtures at this ratio do not meet the required strength within three days of age and should be avoided unless further optimization is possible.
(d) Focus on Workability Parameters: ensure the selected concrete mixtures maintain good slump values and do not set slowly over 120 minutes. Concrete mixtures such as OPC 0.28 AD2, OPC 0.30 AD1, OPC 0.32 AD2, HCN 0.28 AD2, HCN 0.30 AD2, and HCT 0.28 AD1 have demonstrated these qualities and should be prioritized.
(e) Relax Strict Maximum Slump Loss Criteria: reconsider the strict slump loss criterion of 20 mm in two hours, as effective concrete mixtures like HCN 0.30 AD2, OPC 0.28 AD1, and OPC 0.28 AD2 exceed this limit, therefore they did not perform well overall.
(f) Create Balance Performance and Sustainability: encourage the use of hydraulic cement-based concrete due to its lower CO_2 emissions compared to OPC-based concrete. This approach aligns with sustainability goals and reduces the environmental impact of transportation infrastructure projects, in other words, it supports sustainability objectives while ensuring that performance characteristics meet project-specific requirements.

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Nomenclature

CO_2e	Carbon dioxide emission
GHG	Greenhouse gas
FS 45	Flexural Strength of 45 kg/cm^2 (4.50 MPa.)
OPC	Ordinary Portland Cement
HC	Hydraulic Cement
bwc	by weight of cement
w/c	Water to cement ratio
AD1	Admixture-1
AD2	Admixture-2
HESC	High early-strength concrete

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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