# Early Age Strength of Development Ultra High-Performance Concrete Using Class-F Fly Ash and Local Materials for Repair

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**Abstract**

Ultra High-Performance Concrete (UHPC) is an innovative material for such repairs because of its superior mechanical properties, strength, crack resistance, and durability. However, its high production cost, primarily due to using materials like silica fume and cement, is a significant drawback. This study explores the feasibility of incorporating fly ash and local materials into UHPCs to reduce costs while maintaining or improving their performance. As a supplementary cementitious material, fly ash enhances the compressive strength and workability of UHPC. The addition of limestone further supports early-age strength and workability. By evaluating the mechanical properties and workability of modified UHPCs, this research demonstrates the economic viability and environmental benefits of structural repairs. The results indicate that this modification can effectively enhance the early-age strength of UHPC, making it suitable for use as a repair material. The evaluation of the mechanical properties and workability of the modified UHPC suggests that these alternative materials can maintain or even improve the performance of UHPC. Thus, this approach offers a more economically viable and environmentally friendly solution for structural repairs.

*Keywords:* Early age strength; Flowability; Fly ash; Repair Material; UHPC

## 1. Introduction

The American Concrete Institute (ACI) 239R-18 report on Ultra-High-Performance Concrete (UHPC): An Emerging Technology describes UHPC as a superior class of cementitious material characterized by significantly higher strength, tensile strength, and durability compared to conventional and high-strength concrete [1]. More than 20 years ago, UHPC attracted significant interest from the construction sector, focusing on several applications such as bridge construction, unique architectural designs, skyscrapers, damaged concrete components, vertical elements (e.g., wind turbine towers), facilities related to the gas and oil industry, offshore construction, hydraulic structures, and overlay materials [2]. UHPC can generally be used in major structural components, connections between prefabricated components, and repair applications [3].

UHPC is a cement-based structural material considered for structural repair because it can significantly improve mechanical properties, strength, crack resistance, and durability and allow for a lighter reinforcement layer [4]. UHPC also has workability in the 200 – 250 mm range, which typically has a consistency like self-consolidating concrete [1]. UHPCs are innovative for bridge construction and repair. It can be used for rehabilitating bridge deck overlays, structural patching, and repairing bridge elements, as well as for jackets for columns and drive piles [5]. UHPC combines cementitious materials and steel fibers with high mechanical properties, with compressive and tensile splitting strengths exceeding 120 and 5 MPa [6]. The general composition of UHPC includes cement, silica fume (SF), fine aggregates, and steel fibers. This composition contributes to UHPC's main drawback, namely, its high production cost. Therefore, developing alternative materials for UHPC is crucial for reducing production costs. Thus, this research aims to eliminate using materials such as silica fume, quartz powder, quartz sand, and steel fiber in developing UHPC mixtures. Instead, fly ash, limestone, and polyamide fiber are used. It is known that most previous studies related to UHPC still included silica fume, quartz powder, quartz sand, and steel fiber as constituent materials [7]–[12]. Therefore, this study experiments with excluding silica fume as a constituent material, replacing it with fly ash and limestone, and observes its effect on the early compressive strength of UHPC.

This study developed UHPC materials by incorporating fly ash as a supplementary cementitious material (SCM). It also reduces the amount of fly ash, which is a fine residue produced by coal combustion. Additionally, using fly ash can decrease the use of cement because cement production can make a lot of carbon dioxide ($CO_2$) emissions. Fly ash can act as an SCM due to its pozzolanic reaction, which improves structures' mechanical properties and durability [13]. The effect of fly ash can enhance the compressive strength and reduce the porosity in the middle and late ages of UHPC [14]. Using 30% fly ash and 20% silica fume in UHPC results in a compressive strength of 126.6 MPa at 28 days [15]. However, using silica fumes is one of the reasons for the high production cost of UHPC. To address this, limestone ($CaCO_3$) is added to enhance the compressive strength of UHPC. Limestone can improve the early strength of concrete owing to its nucleation effect. Limestone powder can act as nucleation sites for precipitating C-S-H and reduce the nucleation barrier, thereby promoting the early hydration of cement [16]. This can support using UHPC as a repair material because early-age strength is crucial for repair. The use of finer limestone can also enhance workability and reduce porosity. Limestone can fill the crevices and voids between cement particles [17]. The fine aggregates used in this study were local aggregates without adding any other fine aggregates.

This study aimed to investigate the feasibility of modifying ultrahigh-performance concrete (UHPC) by incorporating fly ash as a replacement for cement and local materials. This modification is expected to reduce the production costs of UHPC and enhance its early-age strength, which is critical for its use as a repair material. By evaluating the mechanical properties and workability of modified UHPC, this study aims to demonstrate that these alternative materials can effectively maintain or improve the performance of UHPC while making it more economically viable and environmentally friendly for structural repairs.

## 2. Materials and Method

### *2.1. Materials*

This study made adjustments to enhance UHPC by using local materials and fly ash as supplementary cementitious materials. In addition, limestone ($CaCO_3$) was also used to improve the early compressive strength of the UHPC. Table 1 compares of the material variations in this study with those in ACI 239R-18 on Ultra-High-Performance Concrete: An Emerging Technology Report [1].

Table 1. Comparison of the UHPC Materials used in this Study and the ACI239R

| Materials | ACI 239R-18 | This Study |
|---|---|---|
| Cement | Type 1 cement | Type 1 cement |
| Supplementary Cementitious Material (SCM) | - | Fly ash and limestone |
| Aggregate | Sand | Local Sand |
| Additive Superplasticizer | High-range water-reducer (HRWR) admixture | High-range water-reducer (HRWR) admixture |
| Fiber | Steel fiber | Polyamide fiber |
| Others | Silica fume and quartz powder | - |

Fly ash was obtained from PT PLN Nusantara Power UP Tanjung Awar-Awar, Tuban, in this study. Based on the X-ray fluorescence (XRF) analysis, fly ash was categorized as Class F (details in Table 2), with a CaO percentage below 18%, complying with ASTM C618-19 standards [18]. This fly ash had an hkl phase value of 30.338% based on X-ray diffraction (XRD) analysis shown in Table 3. These results indicate that fly ash contains 30.38% amorphous and 69.62% crystalline phases. Fly ash with high crystalline content is less reactive than fly ash with high amorphous content.

Table 2. Chemical Compositions of Binder Materials

| Materials | Cement (wt%) | Fly Ash (wt%) | $CaCO_3$ (wt%) |
|---|---|---|---|
| $SiO_2$ | 19.45 | 47.04 | 0.01 |
| $Al_2O_3$ | 5.38 | 19.27 | 0.10 |
| $Fe_2O_3$ | 2.95 | 18.46 | 0.09 |
| CaO | 65.13 | 8.89 | 56 |
| MgO | 2.35 | 3.77 | 0.36 |
| $SO_3$ | 2.06 | 0.77 | 0.01 |
| $Na_2O$ | 0.11 | 0.76 | 0.00 |
| $K_2O$ | 0.45 | 0.96 | 0.01 |
| Cl | - | - | - |
| $P_2O_5$ | 0.13 | 0.17 | - |
| $TiO_2$ | 0.28 | 0.95 | - |

Table 3. Crystalin Phase of Fly Ash

| Crystalin Phase | Chemical Formulas | (wt%) |
|---|---|---|
| Lime | CaO | 0.02 |
| Periclase | MgO | 2.51 |
| Quartz | $SiO_2$ | 26.96 |
| Aphthitalite | $NaKSO_4$ | 1.25 |
| Anhydrite | $CaSO_4$ | 2.64 |
| Brownmillerite (Si, Mg) | $Ca_2Fe_{1.2}Mg_{0,4}Si_{0,4}O_5$ | 3.66 |
| Magnetite | $Fe_3O_4$ | 14.41 |
| Hematite | $Fe_2O_3$ | 4.70 |
| Mullite 3:2 | $(Al_2O_3)_3(SiO_2)_2$ | 9.46 |
| Thenardite | $Na_2SO_4$ | 0.74 |
| Diopside | $CaMgSi_2O_6$ | 3.29 |
| Hkl_phase | | 30.38 |

In creating a UHPC mix design, it is essential to understand each material's characterization; thus, material characterization testing is necessary. The specific gravity of the material was used to calculate the material requirements for the UHPC mix. The water-absorption test results for the sand are also required to determine the need for additional water based on the absorption values. If this is not considered, the flowability of UHPC can be affected because the sand absorbs water. The characterization material used in this study is presented in Table 4. The particle size of the material affects the packing density of UHPC, which in turn influences the water demand and flowability of UHPC [19].

Table 4. Characterization Materials

| Characterization | Cement | Fly Ash | $CaCO_3$ | Fine Aggregate (1) | Fine Aggregate (2) |
|---|---|---|---|---|---|
| Specific Gravity ($kg/m^3$) | 3.064 | 2.72 | 2.67 | 2.73 | 2.75 |
| Moisture (%) | - | - | - | 0.026 | 0.029 |
| Absorption (%) | - | - | - | 0.281 | 0.637 |
| Weight Volume (gr) | - | - | - | 1609 | 1387 |

The fine aggregate used in this study is Lumajang sand, a local sand, with two types of sand gradation being used. Figure 1 shows the gradation of sand 1, and Figure 2 shows the gradation of sand 2. Sand 1 indicates that the sand gradation falls within zone 1, meaning coarse sand, while sand 2 falls within zone 1 and zone 2, meaning slightly coarse sand. Both sands in this study are not classified as fine sand, as they are more significant than quartz sand. This type of sand can affect the particle packing density of UHPC [20]. A Particle Size Distribution (PSD) test can be conducted to determine the particle size of each material. However, in this study, only the particle size of the binder material using a 45-micron sieve (%) was tested, as shown in Table 5. According to the test results, limestone had the smallest particle size, whereas cement had the largest. The variation in particle size between cementitious materials and aggregates improves the packing density of UHPC. Cementitious pastes can fill the voids formed among aggregates. Enhancing the aggregate packing density reduces the paste required to fill these voids. Consequently, more paste will be available for a given amount to improve workability. Alternatively, to achieve the same workability level, the paste amount can be reduced [21].

Table 5. Particle Size of Binder Material with 45 Micro Sieve

| Materials | Cement % | Fly Ash % | $CaCO_3$ % |
|---|---|---|---|
| Vol. Under 45 µ | 89.59 | 69.48 | 16.44 |
| Vol. Over 45 µ | 10.41 | 30.52 | 83.56 |

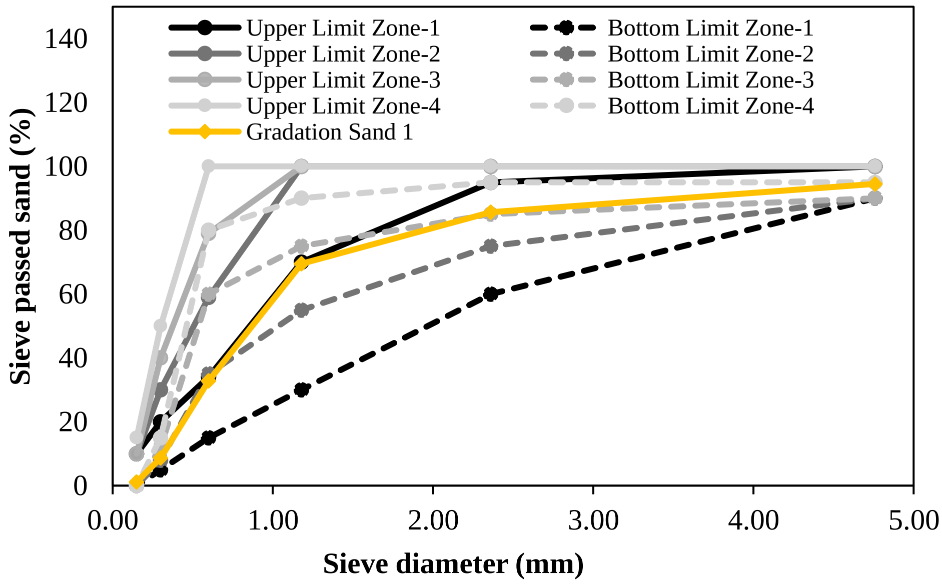



Figure 1. Fine Agreggate 1 Sieve Analysis

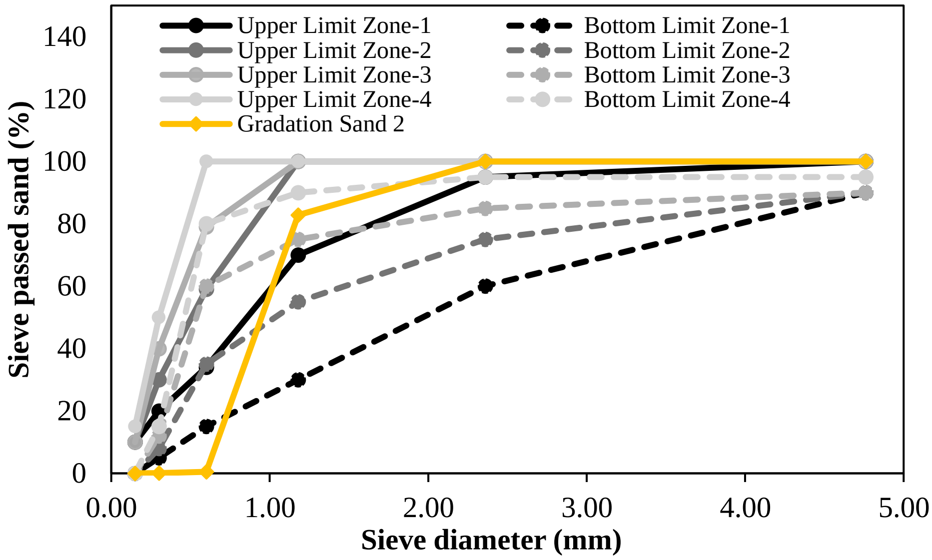



Figure 2. Fine Aggregate 2 Sieve Analysis

### *2.2. Mix Design*

In developing a mixed design to achieve the desired UHPC performance, the method was based on the research of Meng et al. [22]. This method involves six steps: (1) This approach begins by selecting the materials and binder composition based on flow characteristics and particle packing. (2) The water-to-binder (w/b) ratio is determined from 0,15 to 0,25. (3) Determine the proportion and combinations of sand; (4) Determine the Volume Binder to Volume Sand (Vb/Vs) ratio of UHPC; (5) Determine the fiber content of UHPC; and (6) Adjust the w/b ratio and HRWR. Flowability testing was conducted after completing all these steps with a target value between 200 and 250 mm based on ASTM C1856M [23]. If the desired flowability value is not achieved, adjustments can be made to the w/b ratio, HRWR, or Vb/Vs ratio.

### *2.3. Mixture Proportion*

Table 6 shows the UHPC's mixture proportion results determined through the six-step mix design process. This study's variation involves using fly ash as a supplementary material for cement. Since the mixture is intended as a repair material, the 1-day compressive strength is crucial according to ASTM C928 [24]. In this context, fly ash influences the superplasticizer needed to achieve the 1-day compressive strength.

Table 6. Mixture Proportion of UHPC

| **Materials** | **UHPC0FA** ($kg/m^3$) | **UHPC30FA1** ($kg/m^3$) | **UHPC30FA2** ($kg/m^3$) |
|---|---|---|---|
| Vb/Vs | 1.2 | 1.2 | 1.2 |
| Cement | 847.97 | 667.94 | 562.58 |
| $CaCO_3$ | 63.82 | 64.04 | 62.50 |
| Fly Ash | 0 | 183 | 267.90 |
| Water | 182.36 | 183 | 178.60 |
| HRWR | 18.24 | 9.15 | 17.86 |
| Sand 1 | 744.69 | 744.69 | 744.69 |
| Sand 2 | 499.86 | 499.86 | 499.86 |
| Polyamide Fiber | 2.28 | 2.28 | 2.28 |

### *2.4. Mixing and Curing*

The mixing process of UHPCs generally differs from that of conventional concrete mixing. According to ACI 239R [1], due to the low water content of UHPC and no or little coarse aggregate, higher energy input is necessary to disperse the water and overcome the low internal mixing action. These problems are due to the poor transport properties of fluids without following their usual path through coarse aggregates. Blending all binder components to homogeneity is the first mixing step. Water and a superplasticizer are then added. The mixing continued until the dry materials became fluid mixtures. Higher energy was required to mix all materials until homogeneous at this stage because the resulting mixture had a very dense texture. Once fluid, the fibers were mixed until they were evenly dispersed throughout the mixture. After fiber dispersion, the mixing is complete, followed by a flowability test. If the flowability value meets the standard, the mixture can be cast.

With the following exception, they are curing UHPCs for laboratory-fabricated specimens by ASTM C192M. ASTM C192M explained that the treatment of the remolded specimen should be moist cured. Moist curing means the test specimens must always have complimentary water on the entire surface. This condition is met using a water storage tank specified in ASTM C511 [25]. The water storage tank is the water in a storage that is saturated with calcium hydroxide to prevent leaching calcium hydroxide from the specimens.

Figure 3. Mixing UHPC

Figure 4. Water Storage Tank Curing with $Ca(OH)_2$

### *2.5. Early Age Strength Testing*

The tests conducted for early strength included the flowability of fresh concrete and compressive strength at 1, 3, and 7 days. Flowability testing was performed according to ASTM C1856M [1] in the 200 – 250 mm range. The mold (Figure 5) and flow table must meet the requirements of standard ASTMC230 [26] without a concrete pedestal and cork gasket. The mold was filled with a single layer of fresh UHPC; tamping of the mold was not allowed, and the table should not be dropped. After Lifting the mold, wait until a time of 2 min + 5 s; then, the diameter of the UHPC was measured along the lines of maximum and minimum diameter. The compressive strength testing method was according to ASTM C39M [27], but the value must achieve the requirements of ASTM C928M for repair material specifically for structural repair. The compressive strength values for each testing age are shown in Table 7.

Table 7. Early Age Compressive Strength Requirements for Repair Materials

| **Testing** | **Compressive Strength (MPa)** | | |
|---|---|---|---|
| | **1 day** | **3 day** | **7 day** |
| Non-Structural Repair | 3,5 | 14 | 28 |
| Structural Parsial Repair | 7 | 21 | 28 |
| Structural Repair | 21 | 35 | 35 |

Figure 5. Mold Flowability Test

## 3. Results and Discussion

### *3.1. Flowability Test*

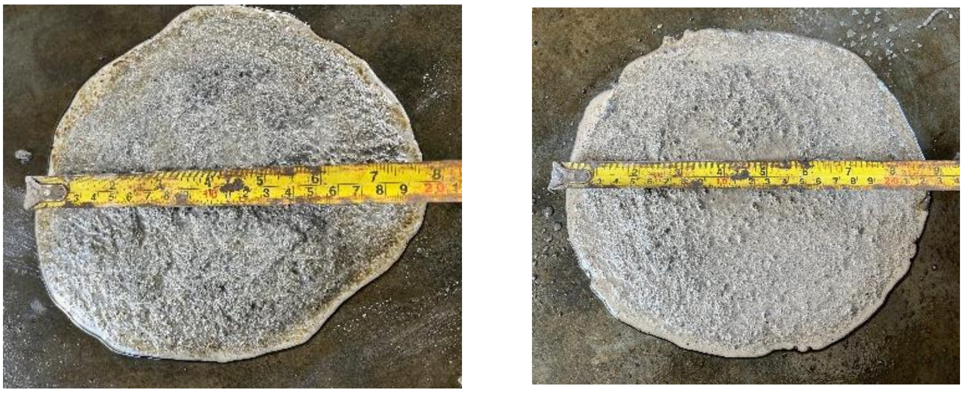
Flowability testing was performed according to the test method ASTM C1437, without dropping the table, to determine the workability of fresh UHPC. The result of the maximum and minimum diameters of UHPC is presented in Table 8. In this study, the diameter of the flowability test was measured on four sides. The UHPC mixture containing fly ash as a supplementary cementitious material was tested twice using two variations of the HRWR: 1% (UHPC30FA1) and 2% (UHPC30FA2). However, for the mixture without fly ash (UHPC0FA), the experiment was only conducted with 2% HRWR variation because trial results showed that the 1% variation did not allow the mixture to flow during the flowability test shown in Figure 6.

Table 8. Flowability Testing Results of UHPC

| **Flow** | **UHPC0FA (mm)** | **UHPC30FA1 (mm)** | **UHPC30FA2 (mm)** |
|---|---|---|---|
| 1 | 185 | 210 | 200 |
| 2 | 195 | 220 | 220 |
| 3 | 195 | 215 | 220 |
| 4 | 185 | 175 | 210 |
| Average | 190 | 205 | 213 |

The UHPC variant containing fly ash met the 200-250 mm flowability test requirements. Fly ash has a spherical morphology, acting as a "ball-bearing" effect that improves the flowability of UHPC [28]. The high flowability resulting from adding fly ash can be explained by the slurry and ball-bearing effects of the superfine fly ash particles [29]. On the other hand, the UHPC without fly ash did not meet the requirements, achieving only 190 mm but was close to 200 mm. This is because the particle size of cement is more significant than that of fly ash, shown in Table 5, the particle size of binder materials. The addition of fly ash results in UHPC with a variation in the particle sizes of the binder materials, which increases the packing density of UHPC by filling the voids between the aggregates [21]. The high packing density will require less water to fill the voids between the solid particles; therefore, at the same w/c ratio, it will release more water to form a water layer that coats the solids to lubricate the paste. The paste will become more flowable and workable, thereby improving the workability of UHPC [30]. The addition of HRWR improved the workability of UHPCs without fly ash and increased its value to 190 mm. UHPC treated with fly ash increased the flowability by 1 cm, resulting in a nearly uniform diameter from all sides. This is because the function of HRWR is to improve the workability of mixtures with low water-cement ratios, such as UHPC. However, paying attention to the maximum dosage is necessary to avoid segregation in the mix [31].

Figure 6. Flowability of Trial UHPC 0% Fly Ash 1% SP



(a) (b)

Figure 7. (a) Flowability UHPC 0% Fly Ash; (b) Flowability of UHPC 30% Fly Ash

### *3.2. Compressive Strength*

The early-age compressive test in this study referred to ASTM C39, and the results referred to ASTM C928 for repair materials. The test specimens were 75 mm x 150 mm cylinders, by ASTM C1856 for UHPC. Testing using a Universal Testing Machine (UTM) is shown in Figure 9. The early age compressive strength result presented in the test results indicates that UHPC without fly ash has demonstrated that this mix can be used as a repair material because it meets the test standards at all testing times. However, in the presence of 2% HRWR, the compressive test value on day 1 for the fly ash mix did not meet the standards for repair materials. This is because the Type F fly ash used in this study, which has a low HKL phase value, exhibits low reactivity. Type F Fly Ash has lower hydration due to its lower hydraulic activity than plain cement. For this reason, early-age strength is slow, even at low replacement levels [29]. The HRWR dosage was reduced specifically for mixes containing fly ash to address this issue. Reducing the HRWR dosage by 1% increased the 1-day test value for fly ash mixes. However, the early-age strength of UHPCs with fly ash was lower than that of UHPCs without fly ash.

Table 9. Early Age Compressive Strength Test Result

| **Testing** | **Early Age Compressive Strength (MPa)** | | |
|---|---|---|---|
| | **1 Day** | **3 Day** | **7 Day** |
| UHPC0FA | 15,92 | 52,97 | 65,94 |
| UHPC30FA1 | 29,80 | 50,55 | 60,89 |
| UHPC30FA2 | 0,23 | 51,08 | 56,51 |


Figure 8. Universal Testing Machine (UTM)

## 4. Conclusions

This study determined the flowability and early-age compressive strength of UHPCs prepared using different materials according to the ACI239R standard. UHPC, with material modifications using fly ash and limestone as supplementary cementitious materials (SCM) and local materials, produces early compressive strength that meets the requirements of a local material. Among the three variations tested, the UHPC30FA1 variation meets the requirements as a structural repair material, with a 1-day strength of 29.80 MPa, surpassing the minimum requirement of 21 MPa. The 3-day and 7-day strengths are 50.55 MPa and 60.89 MPa, respectively, exceeding the minimum requirement of 35 MPa. The flowability value of UHPC30FA1 also meets the flowability requirements, with an average diameter of 205 mm, within the required flow range of 200 - 250 mm. It is known that the use of fly ash and HRWR significantly affects the early strength and flowability of UHPC. The optimal use of fly ash and HRWR was found in the mixture with 30% fly ash and 1% HRWR.

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