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Effect of polypropylene fibers on unrestrained early age shrinkage of concrete and long-term performance subjected to fire

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Abstract. Micro cracks at early age concrete very difficult to avoid although treatments have always been managed. This study focuses on the role of polypropylene fibers of concrete mixtures during first 24 hours after casting. Further investigation has also been carried out to investigate long-term performance of concrete subjected to fire.Size model of 60 mm x 100 mm x 1000 mm was employed investigating the plastic shrinkages,and 50 mm x 200 mm x 350 mm was used to examine concrete micro-cracks. Five polypropylene dosages variations of 0.1%, 0.2%, 0.3%, 0.4%, and 0.5% to the mortar volume were applied. Whilst, cylindrical specimen of Ø150 mm x 300 mm has been conducted with five variations of 0, 1.5, 2.0, 2.5, and 3 kg/m^3 polypropylene dosages to investigate concrete performance under various temperatures. Test results indicate the addition of polypropylene fibers play significant role to reduce cracks and plastic shrinkage. The 0.3% of polypropylene fibers reduces shrinkage losses to 90%. Under elevated temperature, the addition of polypropylene has less significant effect on normal concrete but has very significant effect on high-strength concrete. The high-strength concrete with 2.0 kg/m^3 polypropylene dosage under temperature of 300^{O}C and 700^{O}C has 90% and 35% residual strength, respectively. Therefore, minimum value of 2.0 kg/m^3 polypropylene addition to the concrete mixture is recommended.

Keywords: Concrete; polypropylene; plastic shrinkage; elevated temperature.

1. Introduction

Concrete is a composite material composed of gravel, sand, cement, water and other additional materials. The behavior of the material at early age of the concrete will affect its performance and durability throughout its service life. Although concrete maintenance is always carried out after casting, small shrinkages will be difficult to avoid. This shrinkage began to occur several hours after the fresh concrete was cast in the mold due to water loss and evaporation. If small shrinkages are held by the concrete structure, the tensile stress will occur in the concrete. This tensile stress has the potential to cause small cracks (micro cracks) on the concrete surface. These small cracks are called plastic shrinkage cracks.

The plastic shrinkage crack occurs non-uniformly and is difficult to see on the concrete surface. This crack will open the attack of aggressive chemicals such as CO2, O2 and other acids that are detrimental to concrete. As a consequence, there will be a decrease in the performance and durability of concrete in the long term. The most significant decrease in concrete performance is the decrease in the ratio of the tensile strength to its compressive strength of the concrete. The decrease in this ratio will clearly reduce the elasticity of the concrete and make the concrete a brittle material.

Several studies regarding the addition of fibers have already performed. The most important to note is the parameters that include the type of fiber material, fiber proportion, fiber mechanical properties, fiber dimensions (length and diameter) and the bond strength between the fiber and the concrete mixture.Since polypropylene is a polymeric fiber with a low modulus of elasticity and low adhesion to concrete, testing the elastic modulus, bond strength, tensile strength, size and proportion of the mixture must be clearly identified.

The purpose of the investigation by adding fiber is to reduce water evaporation at an early age of concrete in order to prevent plastic shrinkage. However, the main objective of this study is the prevention of collapse of concrete element structure during fire. The nature of polypropylene which melts at a temperature of 160^{O}C will create pores in the concrete. These pores will flow moisture in the concrete to escape. With the release of this moisture, the concrete will avoid falling out which is caused by the pressure from the water vapor trapped in the concrete. Unfortunately, research on the addition of this fiber has not been widely carried out in Indonesia. For this reason, this research was carried in order to contribute significantly to the perfection of the Indonesian National Standard, especially for high-strength concrete under elevated temperature (SNI 03-1736-2000).

1.1. Micro crack and plastic shrinkage of concrete

Study on the effect of polypropylene fibers on plastic shrinkage and water loss due to evaporation have been done by [1]. The study focuses in the concrete during the first 24 hours after casting by observing fiber dose, fiber adhesion, and fiber stiffness.Concrete specimens of 60 mm x 100 mm x 1000 mm were tested to measure free shrinkage.At the same time, concrete specimens with dimensions of 50 mm x 230 mm x 327 mm were tested to calculate water losses due to evaporation.The test was carried out in a room that is set with high temperature and low humidity to accelerate shrinkage.The doses of polypropylene fibers used in this test varied by 0.1%, 0.2%, 0.3%, and 0.4% of the concrete volume.

The addition of 0.9 kg /m^3 polypropylene fiber to the concrete mixture would slightly increase its flexural strength and increase the hardness index of the concrete.However, the compressive strength and shear strength decreased although not significantly [2].Meanwhile, [3] examined the effect of polypropylene fibers on the tensile strength of normal concrete and high strength concrete.Their experimental results identified that the addition of this fiber slightly reduced the tensile strength of the concrete before 28 days of age.After 28 days of age there is a very interesting effect to note with the increased ability to cover the development of micro cracks in the concrete resulting in increased integrity and density of the concrete.They concluded that adding a small amount of polypropylene fibers to the concrete mixture had a long-term beneficial effect by increasing the tensile strength and durability of the concrete.

Additional variation of 0.2%, 0.5%, 1% and 1.5% polypropylene to the volume of concrete blocks measuring 100 mm x 100 mm x 300 mm was conducted. Significant decrease in the compressive strength of concrete was occured, but on the other hand, the flexural strength increased significantly. Because the main characteristic of concrete is the ability to withstand high compressive strength with low tensile strength, the decrease in compressive strength is considered less important than the increase in tensile strength. So that the addition of polypropylene must be considered as a very important factor to increase its flexural strength [4].

The behavior of concrete blocks with polypropylene fibers was also conducted by [5].The fibers have a length of 24 mm with doses for concrete volumes varying from 0.9, 1.8, and 2.7 kg/m^3.Laboratory testing was carried out by evaluating the mechanical properties of concrete including compressive strength, tensile strength, crack modulus, and flexural resistance.Test result indicated the bending strength of the beam increases 21%, 16.6%, and 23%, respectively.Similar to previous researchers, the additional polypropylene fiber to increase the flexural strength of the concrete structure is recommended.

1.2. Concrete under elevated temperature

In general, when the concrete temperature reaches 100^oC, the cement paste starts to dehydrate because the concrete loses moisture. At this time the particles from the aggregate began to expand causing a large enough strain difference between the particles and causing small cracks to occur in the cement paste. Disintegration in concrete begins at this stage even though the concrete has not experienced a decrease in strength. The strength of the concrete begins to decrease to about 80-90% of its original strength when the temperature increases again to 200^OC. The subsequent increase in temperature to above 300^OC causes the concrete aggregate to start breaking while the strength of the reinforcing steel in reinforced concrete begins to decrease. At this temperature, the strength of the concrete remains 70%. Furthermore, the strength of concrete and steel begins to decrease seriously when the temperature increases between 500^OC and 600^OC with the strength of the concrete remaining 30-40% while the strength of the reinforcing steel remains 50%. In a burning building, the temperature in the concrete can reach 1200^OC when all of the concrete particles turn to ash [6].

The addition of polypropylene fibers is recommended for fire safety design of high-strength concrete structures.This addition is intended to increase the permeability of the concrete under high temperatures.Polypropylene fibers will melt at a temperature of about 160^OC and create a channel to drain the steam pressure in the concrete element.The channeling of the water vapor pressure in the concrete will saves the concrete from falling out.European Standard [7] recommends a minimum dose of 2 kg/m3 of polypropylene fiber to be added to the concrete mixture to prevent spalling. However, the effect of concrete spalling can be neglected if the moisture content of the concrete does not exceed 3% by weight.

Although research on the addition of polypropylene fibers to concrete mixtures has been carried out by many researchers [8], this type of research has not been widely carried out in this country. Unfortunately, the addition of polypropylene fibers to the concrete mixture for building safety under fire has not been regulated by the Indonesian National Standard [9]. Therefore, updating Indonesian's national standards with reference to the findings of recent researchers is highly recommended [10,11].

2. Experimental Program

2.1. Specimens preparation

Coarse aggregate in the form of gravel were classified based on three size variations of diameter less than 5 mm, between 5 and 10 mm and between 10 and 20 mm for the purposes of different components.Concrete mixed design was carried out by considering the compressive strength of the concrete. The mixing procedure in each batch was carried out carefully at the similar time.Mixing dry aggregate in the form of gravel, sand and cement were carried out for two minutes.Slowly add part of the water and mix for four minutes.Then the polypropylene fibers are added slowly and continue mixing for two minutes to ensure a complete distribution of the fibers.Then add all the remaining water and mix for two minutes.The time required for mixing the concrete is about ten minutes.This procedure was carried out consistently throughout the mixing process.

2.1.1. Specimens for micro cracks and shrinkage investigations.

Concrete mortar consists of sand, cement and water was employed in order to examine the plastic shrinkage and micro cracks investigation. The concrete mortar size of 60 mm x 100 mm x 1000 mm was used to investigate the plastic shrinkage.The dosage of polypropylene fiber used in this test has five variations of 0.1%, 0.2%, 0.3%, 0.4%, and 0.5% to the mortar volume. Meanwhile, to examine water loss due to evaporation and plastic cracks of concrete, mortar specimen with dimensions of 50 mm x 200 mm x 350 mm was employed.Similar to the micro cracks investigation, the dosage of polypropylene fiber used in this test has also five variations of 0.1%, 0.2%, 0.3%, 0.4%, and 0.5% to the mortar volume. The test specimen for shrinkage investigations can be seen in Figure 1, whilst Figure 2 presents the test specimens for micro cracks investigations.

Figure 1 Test specimens for shrinkage investigations.

Figure 2. Test specimen for micro cracks investigations

2.1.2. Specimens for elevated temperature investigations. The specimens for elevated temperature investigation with standard cylindrical size of 15 mm diameter and 30 mm height were employed. Various polypropylene dosages of 0 kg/m^3, 1.5 kg/m^3, 2.0 kg/m^3, 2.5 kg/m^3, dan 3.0 kg/m^3 to the concrete volume were utilized. Thetest specimens for concrete under elevated temperature investigation can be seen in Figure 3.

Figure 3. Test specimens for concrete under elevated investigation

2.2. Laboratory setup.

2.2.1. Micro cracks and shrinkage investigations.
The test is carried out in a room set with high temperature and low humidity to accelerate shrinkage and micro cracks. The treatment of the specimens in the room can be seen in Figure 4. Longitudinal shrinkage of the specimen was measured with a length measuring instrumentand micro cracks were scrutinized with a microscope.

Figure 4. Specimens treatment in high temperature and low humidity room

2.2.2. Concrete under elevated temperatures.

The fire resistance test was carried out at concrete 50 days of age.At that time, the condition of the concrete can be said to have low humidity with a balance of moisture content.This balance is achieved if two consecutive weightings carried out at 24 hours intervals do not produce a difference of more than 0.1% of the weight of the test object.Fire resistance test was carried out using a furnace that has a capacity of up to $1200^{O}C$ shown in Figure 5.

Figure 5. Thermo scientific furnacewith capacity up to $1200^{O}C$

Concrete under elevated temperature test were carried out in two various temperatures of $330^{O}C$ and $770^{O}C$ furnace atmosphere.It was estimated that the temperature on the concrete surface will be $300^{O}C$ and $700^{O}C$.These two temperatures will be used as guidelines for further analysis.Each temperature was maintained for 3 hours.After that the temperature was release returns to room temperature of $20^{O}C$ at the concrete surface temperature.The relationship between Time vs Temperature in the furnace can be seen in Figure 6 and 7 respectively.

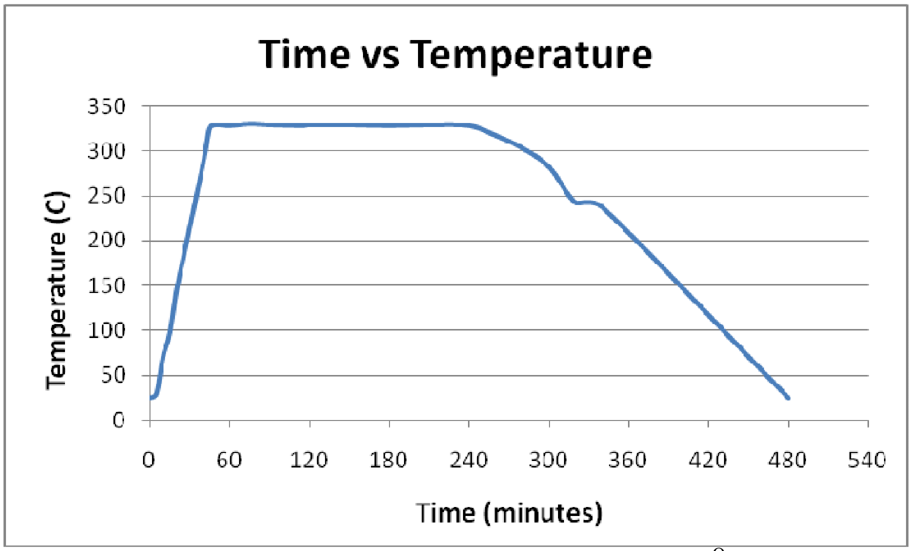

Figure 6. Time-Temperature of furnace up to 330^{O}C

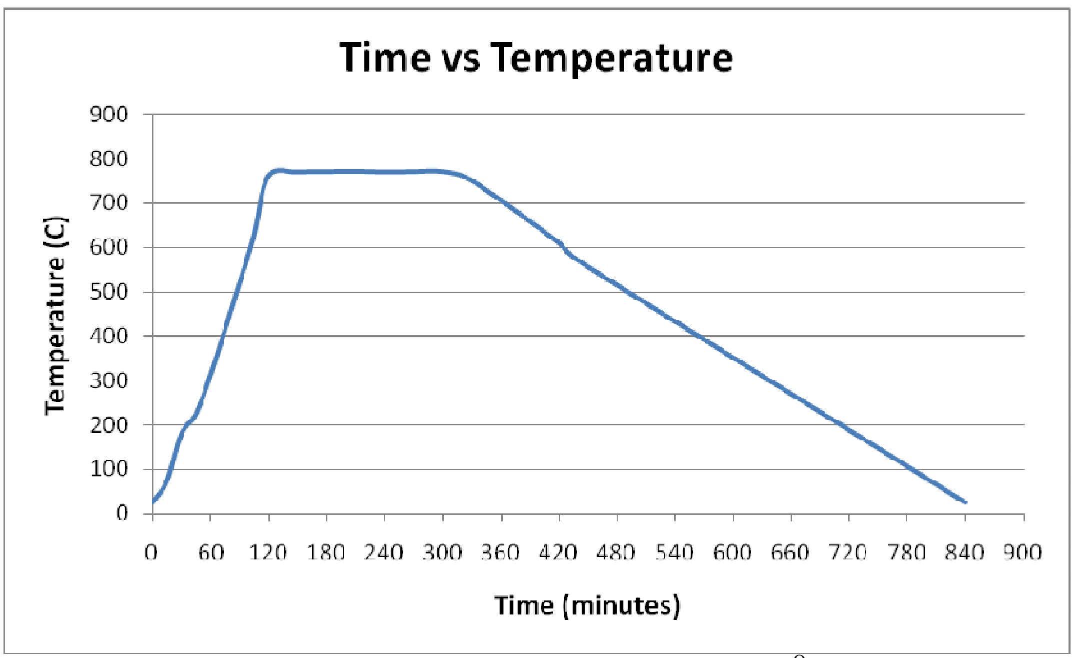

Figure 7. Time-Temperature of furnace up to 770^{O}C

3. Result and Discussion

3.1. Effect of polypropylene fibers on plastic shrinkage and micro cracks in the early age of concrete

Concreteshrinkages began to occur several hours after the fresh concrete was cast in the mold due to water loss and evaporation. Tensile stress will occur in the concrete because these shrinkages are held by the concrete structure. This tensile stress has the potential to cause small cracks (micro cracks) on the concrete surface. Since the micro crack occurs non-uniformly and is difficult to see on the concrete surface, this study will only discuss the effect on concrete shrinkages. The effect of polypropylene fibers on plastic shrinkage at the early age of concrete can be seen in Table 1 explaining the reduction of concrete plastic shrinkage.

Table1 Reduction of plastic shrinkage in the early age of concrete

No	Polypropylene (% Volume)	Plastic Shrinkage Reduction (%)
1	0.0	0
2	0.1	30 - 50
3	0.2	70 - 90
4	0.3	80 - 100
5	0.4	90 - 100
6	0.5	90 - 100

Shown in Table 1, the addition of polypropylene fibers has significant effect to reduce the occurrence of plastic shrinkage in the early age of concrete.Addition of 0.1% fiber to volume will reduce shrinkage by 30-50%.Adding another dose of polypropylene fiber to 0.2% will reduce shrinkage by 70 - 90%.With polypropylene fiber content above 0.3% of the volume fraction, it will reduce the risk of plastic shrinkage above 80%, and it can even completely eliminate the occurrence of shrinkage in concrete.From the results of these observations it is recommended to mix polypropylene fibers with a minimum dose of 0.3% to the volume of the concrete to avoid plastic shrinkage in the early age of the concrete.

3.2. Effect of polypropylene fibers on concrete subjected to fire

The concrete compressive strength tests were carried out in two stages.The control specimen of concrete without fire was carried out at the age of 28 days of concrete.The compressive strength of control specimen concrete with a concrete surface room temperature of 20^{O}C have been compared to concrete compressive strength after elevated temperatures of 300^{O}C and 700^{O}C. Table 2 presents the test results for normal concrete while Table 3 shows the test results for high strength concrete.

Table 2. Residual compressive strength of normal-strength concrete under elevated temperature

No	Polypropylene	Compressive Strength (MPa)			Residual Compressive Strength (%)	
	(kg/m³)	20^{O}C	300^{O}C	700^{O}C	300^{O}C	700^{O}C
1	0.0	29.87	25.76	9.12	86.24	30.53
2	1.5	30.93	25.77	8.35	83.32	26.99

3	2.0	28.72	24.73	8.89	86.11	30.95
4	2.5	28.80	23.36	7.12	81.11	24.72
5	3.0	28.47	24.12	7.35	84.72	25.82

Table 3 Residual compressive strength of high-strength concrete under elevated temperature

No	Polypropylene	Compressive Strength (MPa)			Residual Compressive Strength (%)	
	(kg/m³)	$20^{O}C$	$300^{O}C$	$700^{O}C$	$300^{O}C$	$700^{O}C$
1	0.0	42.09	36.55	10.51	86.84	24.97
2	1.5	39.35	34.79	13.73	88.41	34.89
3	2.0	44.63	40.36	15.54	90.43	34.82
4	2.5	34.44	28.17	9.57	81.79	27.79
5	3.0	35.67	30.53	7.19	85.59	20.16

Tables 2 and 3 displayed the decrease in concrete strength due to an increase in temperature occurs in all variations of concrete.Unfortunately, in this study not all expected concretestrengths were fulfilled.Since the high-strength concrete is defined as a concrete with compressive strength ≥ 40 MPa, there were only three sample groups that qualified into the high-strength concrete category, i.e. specimens with polypropylene content of 0%, 1.5% and 2.0%, respectively.Meanwhile, those with doses of 2.5% and 3.0% can be categorized as normal-strength concrete.

At temperatures of $300^{O}C$ and $700^{O}C$, the highest resistance to fire occurs in high-strength concrete with a polypropylene dosage of 2.0 kg/m^3 which still has residual strength of about 90% and 35%, respectively.In normal concrete, the effect of adding polypropylene has a less significant effect.The residual strength after elevated temperature of $300^{O}C$ ranges from 81-86% while at $700^{O}C$ after fire ranges from 20-30% compared to room temperature concrete strength.

The decrease in strength of concrete is caused by reduction of concrete adhesion as a result of water evaporation in the concrete due to the heating process.The heating process of the concrete is followed by a decomposition process of C-S-H elements into lime free of CaO, SiO and H2O water vapor.The decrease in strength in concrete can also be observed visually by looking at the state of the concrete after the temperature increase.Small cracks happened to the concrete under elevated temperature of $300^{O}C$.Spalling in some parts of the concrete and cracks on most of the concrete surface occurred under elevated temperature of $700^{O}C$.

4. Conclusion

4.1. Concluding remark

Test results and discussions showed thatthe addition of polypropylene fibers has significant effect to reduce plastic shrinkage in the early age of concrete. Under elevated temperature, the addition of polypropylene hasvery significant effect on high-strength concrete but less significant effect on normal concrete.The following conclusions can be drawn:

- Addition of 0.1% fibers to concrete volume will reduce shrinkage by 30-50%.
- Adding another dose of polypropylene fibers to 0.2% will reduce shrinkage by 70-90%.
- Addition of 0.3% or more fibers will reduce the risk of plastic shrinkage by 80-100%.

- The residual strength under elevated temperature of $300^{O}C$ ranges from 81-86%, and at $700^{O}C$ranges from 20-30% for normal-strength concrete.
- The highest residual strength under elevated temperature of $300^{O}C$ was 90%, and at $700^{O}C$was 35% for high-strength concrete with minimum polypropylene dosage of 2.0 kg/m^3.

4.2. Recommendations

Recommendations in the form of suggestions can be expressed as follows:

- Minimum polypropylene dosage of 0.3% should be added to the concrete volume in order to avoid the occurrence of plastic shrinkage in the early age of concrete.
- Minimum polypropylene dosage of 2.0 kg/m^3 should be added to concrete mixed-design of high-strength concrete subjected to fire. This polypropylene dosage has a good agreement to the European Standard [7].

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