# THESIS APPROVAL

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**TITLE:** Plastic Shrinkage Cracking in Fiber Reinforced Concrete

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THESIS

# PLASTIC SHRINKAGE CRACKING IN FIBER REINFORCED CONCRETE

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A Thesis Submitted in Partial Fulfillment of
the Requirements for the Degree of
Master of Engineering (Civil Engineering)
Graduate School, Kasetsart University
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Aminath Ali 2012: Plastic Shrinkage Cracking in Fiber Reinforced Concrete. Master of Engineering (Civil Engineering), Major Field: Civil Engineering, Department of Civil Engineering. Thesis Advisor: Associate Professor Prasert Suwanvitaya, Ph.D. 100 pages.

The purpose of this study was to determine the influence of fiber on the cracking tendency of concrete at early age. Steel and polyvinyl alcohol fibers were used in varying dosages in two strength concrete mixes to study the restrained shrinkage cracking and unrestrained shrinkage that occurred in the early ages. The FRC specimens were compared with fiber-free control specimens for difference in shrinkage and cracking as well as split tensile strength.

Results indicate a very significant reduction in restrained shrinkage cracking with fiber volume fractions between 0.05%- 0.15% by volume. Almost 90% reduction of cracking was observed in PVA fiber and nearly 50% in steel fiber with 0.15% fiber volume.

Free shrinkage tests showed a light decrease in length for all mixes, with 0.15% PVA mix being the most significant. The results were not as consistent as expected, and the reduction of cracking observed in the mixes may be due to a combination of low shrinkage reduction and crack bridging properties of fibers. The tensile capacity of steel fiber concrete was slightly higher than that of PVA fiber concrete, but FRC mixes did not show improvement in tensile capacity when compared with unreinforced concrete.

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Student's signature Thesis Advisor's signature

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# LIST OF ABBREVIATIONS

| | | |
|---|---|---|
| FRC | = | Fiber Reinforced Concrete |
| ASTM | = | American Standard Testing Method |
| ACI | = | American Concrete Institute |
| PVA | = | Polyvinyl alcohol |
| SF | = | Steel Fiber |
| PP | = | Polypropylene |
| SFRC | = | Steel Fiber Reinforced Concrete |
| mm | = | Millimeters |
| cm | = | Centimeters |
| µm | = | Micrometers |
| $mm^2$ | = | Square Meters |
| m | = | Meters |
| KN | = | Kilo Newton |
| N | = | Newton |
| $m^2$ | = | Square Meters |
| kg | = | Kilogram |

# PLASTIC SHRINKAGE CRACKING IN FIBER REINFORCED CONCRETE

## INTRODUCTION

Concrete is a brittle material by its nature. It is capable of withstanding great compressive stresses, but is limited by the low tensile capacity. To allow concrete to withstand high tensile stresses, we use steel reinforcement, which has high tensile capacity. Nevertheless cracking still occurs, even in the most carefully built structures due to other mechanisms that cannot be fully controlled.

Cracking occurs when the tensile stress developed in the member exceeds the tensile capacity of the material. In fresh concrete, even before it has begun to set, there are mechanisms occurring in the mixture, that cause stresses to occur in the concrete.

The hydration process of fresh concrete itself causes change in volume of the concrete itself. If the concrete is allowed to expand and contract without any form of restraint, it will not crack because these stresses are not restrained. However even fresh concrete, at its earliest age also has some internal restraints which usually cause minute cracking.

These early age effects can be broadly divided into two stages. First, cracking that occurs before initial setting is complete (i.e. concrete is in a fluid or semi-fluid state), and secondly, cracking that occurs after the concrete has begun to set (RILEM TC 181-EAS, 2003). In the plastic stage (or the early age), plastic shrinkage cracking and plastic settlement cracking cause the most significant problems.

Before hardening, cracking occurs due to plastic settlement and plastic shrinkage cracking of the concrete. After hardening, numerous causes could cause cracking. They could be structural cracks due to loading and creep, thermal cracks, and chemical cracks which occur due to corrosion and carbonation or physical cracking which occurs due to drying shrinkage. (Concrete Society, 1992)

In normal practice, these cracks are not usually visible to the naked eye. However they are dangerous because they allow ingress of water and other aggressive chemicals into the member. In large surface area applications such as floor slabs, slab on grade and bridge decks, these tiny cracks cause the most damage because reinforcement is within easy reach and the depth of the members are so thin.

In this study, specimens were uniaxially restrained and allowed to crack, to investigate the behavior of different FRC mixes. Other researchers have observed that fiber reduced the cracking tendency of concrete, but due to the cost limitations and lack of research and standards, field applications are not as popular as they could be. The effect of very low fiber content (less than 0.5%) was rarely studied in the past.

# OBJECTIVES

This study aims to evaluate the effectiveness of steel fiber reinforced concrete in preventing early age shrinkage cracking in concrete through experimental studies. The specific objectives are:

1. To find out the reduction of shrinkage achieved by comparison of plain concrete and fiber reinforced concrete with various fiber dosages.

2. To determine the workability and variation in tensile strength of fiber reinforced concrete in comparison to normal concrete.

3. To determine the effect of steel and polyvinyl alcohol fiber on early shrinkage cracking behavior with different fiber content.

## Scope of Research

The study consists of experimental tests conducted on FRC specimens and plain concrete specimens to study the following properties:

1. Uniaxially restrained shrinkage test will be conducted to study the relative cracking potential of different mixes exposed to similar drying conditions.

2. Free shrinkage tests will be done to evaluate the natural free shrinkage behavior of the same mixes and splitting tensile tests will be conducted to evaluate the tensile strength of the mixes.

3. Besides these, fresh concrete tests to establish the basic engineering properties of these concrete mixes will be conducted.

# LITERATURE REVIEW

## 1. Introduction to Shrinkage

Shrinkage of concrete can be defined as the reduction in volume of the concrete with time. Shrinkage in concrete is divided into two stages, 'Early age' shrinkage and 'long term' shrinkage. Early age shrinkage occurs during the first 24-hour only. During this time the concrete is fluid but undergoes stiffening from the outside in. Initial hardening occurs on the surface, but it takes several hours for the concrete to harden. Figure 1 shows the rigidity of concrete with time.

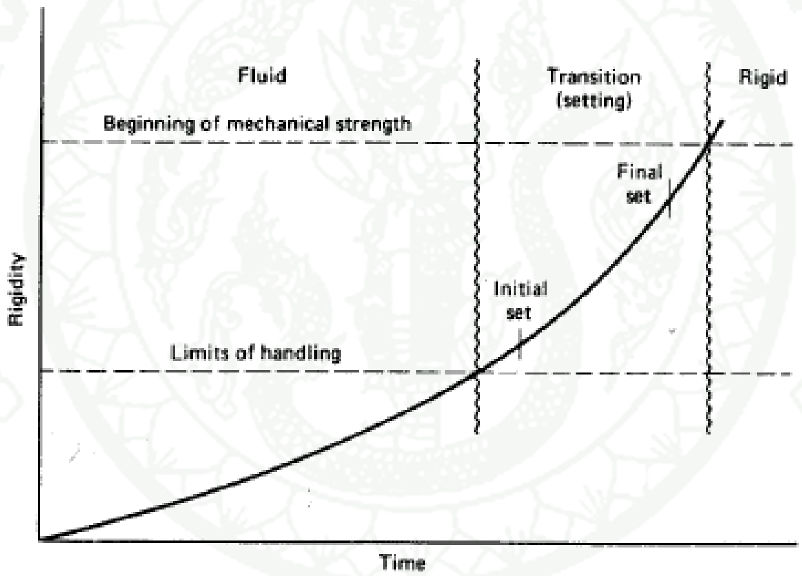



**Figure 1** Early age phases of concrete

**Source:** Mehta and Monteiro (1993)

Shrinkage cracking is not entirely preventable. Although these processes continue for years, the most significant amount of shrinkage is undergone within the first 3 months. There are several types of shrinkage processes going on in the concrete such as plastic shrinkage, drying shrinkage, autogenous shrinkage, thermal contraction, carbonation, and chemical shrinkage. However in this study we will focus on the early age shrinkage of concrete only.

**2. Types of Shrinkage**

2.1 Plastic Shrinkage (Early Age Shrinkage):

Plastic shrinkage refers to the volume change that occurs during the first few hours of fresh concrete. Plastic shrinkage cracks usually occur on horizontal surfaces, which are usually parallel to one another. They affect the aesthetics of the structure, and allow water and chloride penetration, which in turn, reduce durability and cause significant structural problems later in time.

Plastic shrinkage occurs when the rate of evaporation of the bleed water from the surface is faster than the rate of bleeding itself. As the heavier elements in the concrete mixture try to recede to the bottom, the water bleeds up. If the surface of the concrete dries out, menisci forms between the solid particles and capillary tension forces occur. As a result, surface cracking develops. (Concrete Society, 1992).

Cracking which occurs due to settlement of solids after the concrete is laid, is called plastic settlement. These cracks are usually seen in deeper sections such as walls, columns and deep beams.

The primary cause of plastic shrinkage cracking is, rapid drying out of the concrete surface. This rapid drying out occurs ideally when the ambient temperature is warm, dry and the air velocity is high. The most popular method of crack mitigation is wet curing during the first few days to prevent surface dry-out. These methods, though effective for some environments, are not practical for warm climates.

2.2 Autogenous Shrinkage

Autogenous shrinkage is the reduction of volume of concrete that occurs due to macroscopic volume changes in the matrix, without any moisture transfer to the environment. These changes occur due to chemical reactions and cannot be avoided. In the early days of concrete research, this type of shrinkage was seen as insignificant, mostly because there was no standard method to check and measure this behavior (Holt, 2001).

In normal concrete applications, the autogenous shrinkage component contributes very little to the total shrinkage of the concrete. Therefore it is commonly treated as part of the drying shrinkage. (Tritsch *et al.*, 2005) But, in high strength concretes and those with low water-cement ratios, autogenous shrinkage could exceed drying shrinkage. (Newman and Choo, 2003)

## 2.3 Drying Shrinkage:

As concrete hardens, the water contained in the concrete member and the water vapor contained in the surrounding air will reach equilibrium. This is achieved by either, evaporation of water from the concrete or, adsorption of the water vapor into the concrete. Initially, water held in the capillary pores is lost, but this doesn't cause much volume change. Then, the water contained in the tiny capillary pores as well as the water in the hydrated gel is pulled out. This causes tensile stress to develop in the residual water, and as a result, compressive stress in the adjacent concrete, which causes shrinkage of the member. If the concrete is allowed to shrink without any restrictions, it should not crack. Since concrete structures are generally reinforced, and they contain aggregate (which acts as a restraint), they will crack. In hardened concrete, these cracks can pass through aggregates too. (Newman and Choo, 2003).

Drying shrinkage occurs throughout the life of the structure. The mechanism is well studied and remedial measures are taken by proper detailing and construction methods to minimize the effect of drying shrinkage cracking. It is measured using standardized specimens according to ASTM C157 as change in length over time (As shown in Figure 2).

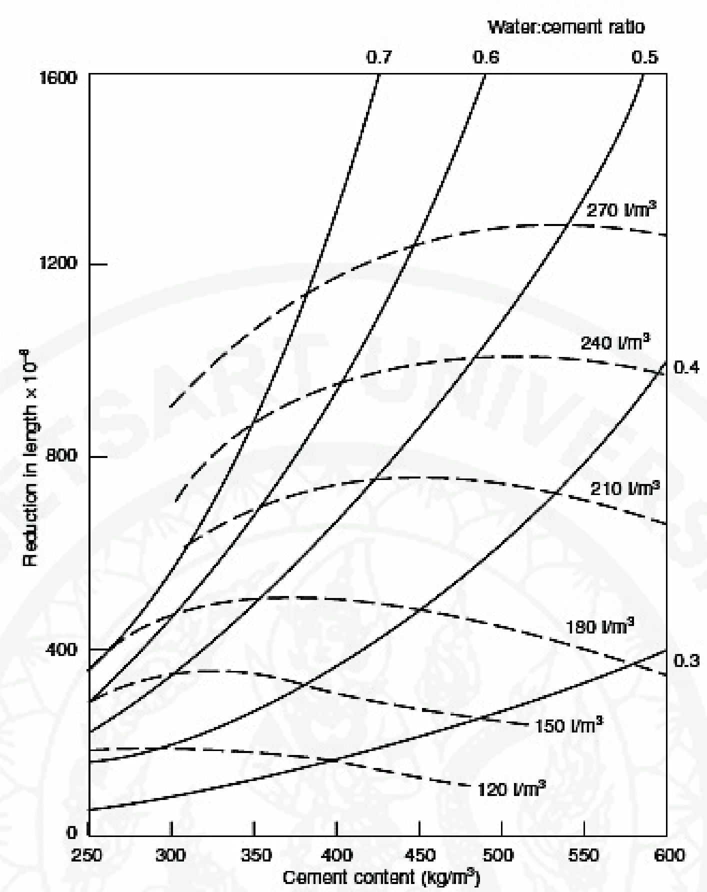



**Figure 2** Drying shrinkage of concrete over six-month duration.

**Source:** Concrete Society (1992)

**3. Factors affecting shrinkage of concrete.**

3.1 Water-cement ratio

Shoya (1979) found that as the water-cement ratio increased, shrinkage also increased. When water content is high, concrete has a lower modulus of elasticity, more free water to bleed to the surface, and as a result, it is more prone to shrinkage. This effect is similarly observed in cement rich concrete as well. The fineness of cement also causes more shrinkage (Mehta, 1994; Cohen *et al.*, 1990). It is logical to assume that longer setting time would also increase crack formation because the concrete would be in its plastic state far longer.

3.2 Aggregate

The quantity of aggregate in the concrete is very important because the aggregate content has much bigger impact on the shrinkage than the w/c ratio. (Neville, 1996) (See Figure 3) Some aggregate shrinks less compared to cement paste, and is more desirable. Aggregate is also important in a different context. When lower quality aggregates are used, they tend to shrink more and have more debris such as clay on them, which cause higher shrinkage.

There are very few studies that study the effect of increasing fine aggregate on crack mitigation. However (Cohen *et al.*, 1990) demonstrated that sand particles appeared to arrest the crack because the cracks do not propagated around the sand particles.

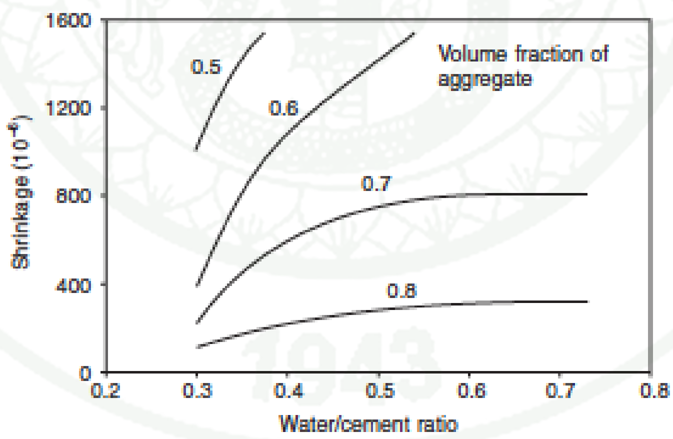



**Figure 3** Effect of w/c ratio on shrinkage for different aggregate content

**Source:** Newman and Choo (2003)

3.3 Admixtures

Admixtures affect the shrinkage depending on the reactions they have with other constituents in the concrete mix. Mineral admixtures such as fly ash and limestone powder improved the shrinkage resistance of concrete, (Tongaroonsri and Tangtermsirikul, 2009). But admixtures containing Calcium Chloride increase the shrinkage of concrete. There are shrinkage reducing admixtures, which are very effective in reducing drying shrinkage (Xi *et al*., 2003)

Plasticizers are usually used to improve the workability of concrete. This is necessary in high fiber volume concrete and the dosage needs to be controlled properly to reduce excessive retardation.

3.4 Geometry

It is undesirable to have larger surface areas and shallow sections in concrete members. Weiss and Shah (2002) studied the geometrical effects on shrinkage in early age concrete and found that amount of shrinkage and the age of shrinkage were both low for thicker sections. Hanson and Mattock (1966) found that shrinkage decreases as the surface/ surface ratio increases and (Uno, 1998) states that deeper sections are less prone to plastic crack formation.

3.5 Relative Humidity

A dry environment causes greater shrinkage. This effect is more compared to the swelling of concrete due to higher relative humidity. Therefore, the relative humidity gradient is an important factor in mitigating shrinkage. Wind speed is also very important for plastic shrinkage because higher wind speed accelerates the evaporation rate and this could cause surface drying at early age (Concrete Society, 1992).

3.6 Curing Method

Controlled curing was the traditional method to prevent curing. This consisted of keeping the concrete moist and covered until it has gained sufficient strength. Some people seal the surface of the concrete to prevent cracks. Altoubat and Lange (2001) found this practice to be ineffective in reducing shrinkage. They found that alternate wetting and curing the early days reduced early age cracking. Proper placing and compaction of concrete is necessary to minimize drying shrinkage. Compaction is necessary to produce dense concrete and less capillary pores.

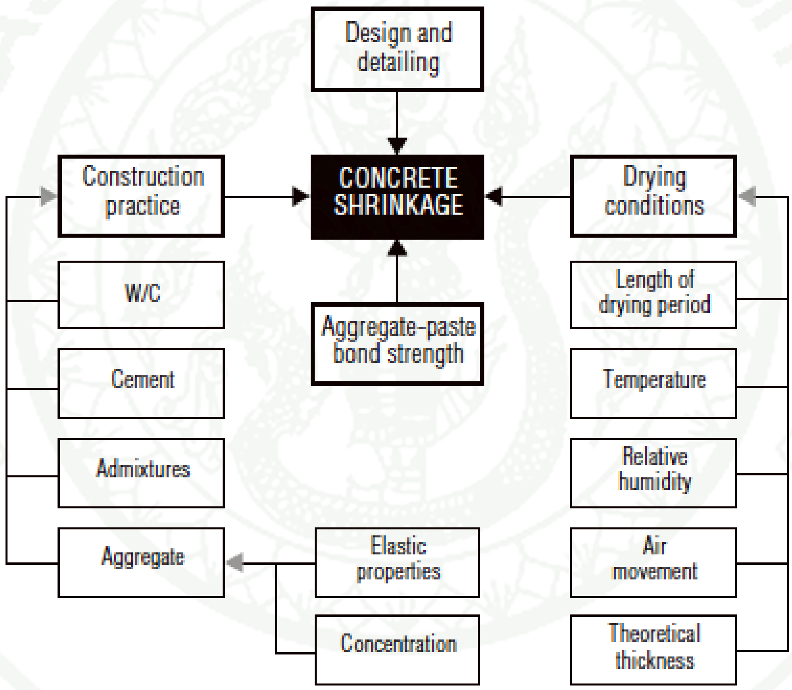



**Figure 4** Factors affecting concrete shrinkage

**Source:** Cement and Concrete Association of Australia (2002)

In addition to the above factors there are some more minor factors that affect cracking, some of which specifically affect the shrinkage cracking of concrete.

3.7 Tensile strain capacity

This is difficult to predict and has negligible effect in case of plastic and autogenous shrinkage cracking. In theory, higher tensile capacity should prevent cracking. In practice, this is extremely difficult to achieve and very little research has been conducted to study this phenomenon. Although FRC has higher tensile capacity, standard tests are not able to show the effect significantly.

3.8 Restraint

If the concrete is allowed to expand and contract at will, it will not crack. But in practical applications this cannot be so. Therefore, we must take into account the restraints present in the member. External restraints can be modified with joints and such, to reduce stress. But internal restraints such as aggregates cannot be avoided; therefore the members have to be designed carefully.

3.9 Reinforcement

Adequate distribution reinforcement ensures that tensile stress developed by the shrinkage is distributed evenly throughout the member. This does not prevent crack forming. But the cracks, if present, are thin and short, and distributed evenly.

3.10 Control joints

These joints allow movement and prevent crack formation. However, they are mostly effective for thermal movement and drying shrinkage. (Cement and Concrete Association of Australia, 2002)

3.11 Fiber reinforcement

Altoubat and Lange, (2001) found that steel fiber reinforcement delayed the fracture of restrained concrete considerably, especially in low w/c ratio concrete.

Banthia *et al*. (1996) confirmed that, at constant temperature and humidity, steel fiber reinforced concrete produced less cracking than normal concrete. Sroushian *et al.*, (1995) studied the effects of polypropylene (PP) fibers on plastic crack formations and concluded PP fibers reduced cracking and crack widths at 0.1% fiber volume. The behavior of steel and propylene (PVA) fibers in mitigating shrinkage cracking will be reviewed in detail in the next section.

**4. Fiber reinforced Concrete**

Fiber reinforced concrete (FRC) consists of short and discrete fibers distributed uniformly throughout the normal concrete mixture. These fibers could be, synthetic organic or synthetic inorganic.

They are found to enhance the natural mechanical properties of concrete depending on the fiber type and concrete used. Though fibers have been used in concrete since the early 40’s, they were not in common use until the 1960s (Li, 2011).

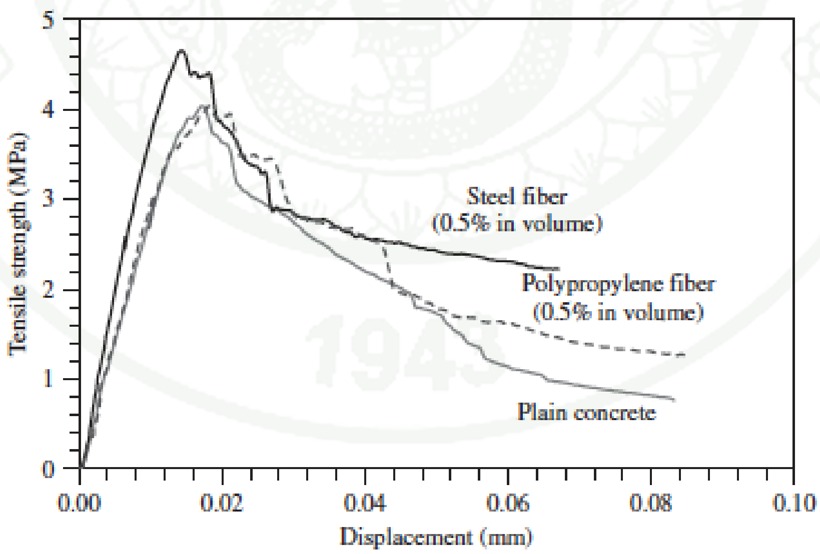



**Figure 5** Load-displacement curves from different types of FRC

**Source:** Li (2011)

Fiber content does not affect long-term shrinkage of concrete members. However, in the early stages of life, before the concrete has gained stiffness and strength, they help by increasing the tensile capacity and toughness of the concrete.

Numerous researches have been done on the effect of fibers and their volume on the behavior of concrete structures. Figure 6 shows a comparison of the loading capacity of different FRC compared with plain concrete and it is clear that steel fiber improves the loading capacity significantly.

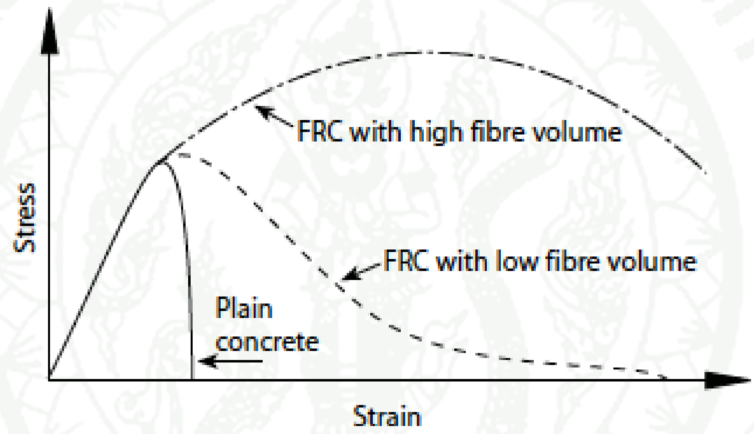



**Figure 6** Typical stress-strain curves for FRC and NC.

**Source:** Cement Concrete Institute (2010)

For this research, only the shrinkage crack formation and reduction properties of these fibers were studied.

4.1 Properties of the fiber

To reduce shrinkage cracking effectively, the fiber must have a tensile capacity greater than that of the concrete matrix. The fiber also needs to have a higher modulus of elasticity than the concrete. Steel fibers are better than polymeric and natural fibers in this respect. Until the concrete gains sufficient stiffness, the fibers help keep the matrix together. Regarding the geometry of the fiber itself, (Johnston, 1992) concluded that the physical and geometrical characteristics such as the size, shape, texture and the aspect ratio of the fiber are also important factors. (Eren and Marar, 2010) contradict by observing that aspect ratio of the fiber does not affect the crack length significantly.

4.2 Workability

Workability is a measure of its ability to be mixed, handled, transported placed and consolidated (ACI Committee 544, 1999). This is a critical issue in FRCs. The dosage rate and the aspect ratio of the fiber play an important role. To remedy this, fibers ate gradually introduced into the mixture as the last ingredient. Tests on the slump of different fiber mixes have shown a strong reduction in the slump of FRC compared with normal concrete. It is common practice to use superplasticizer to improve workability of FRC concrete.

4.3 Plastic shrinkage cracking

The age of first cracking is delayed when low percentages of fibers are added to the concrete. Fibers prevent cracks from widening and propagating throughout the concrete. However, there is no significant reduction in free shrinkage observed with polymer fibers. (Weiss *et al*, 1997). Zhang and Li (2001) used steel fibers to show that long-term shrinkage is reduced in SFRC. The total plastic shrinkage crack area reduced with increased steel fiber volume. (Eren and Marar, 2010). Low volume PVA fibers produce significant reduction in shrinkage (Wongtanakitcharoen *et al.*, 2007), PVA fibers showed improved tensile strength drying shrinkage and reduction in plastic and dry shrinkage cracks (Xiao *et al.*, 2011).

4.4 Strength of concrete

Johnston (1992) observed that compressive strength, flexural strength, toughness and durability are all improved with fiber reinforced concrete. Plastic fibers have a low modulus of elasticity and do not contribute to the strength of concrete after hardening, but steel fibers are consistently proven to be effective in improving strength when the steels fibers are aligned properly. This is not practical in normal applications.

**5. Methods of testing plastic shrinkage cracking.**

Although there is a wide range of tests available to test restrained shrinkage cracking and widely used b researchers, two of these tests have been recently standardized in ASTM C1579 and ASTM C1581. The first test C1579 tests the plastic shrinkage cracking behavior of concrete using a stress riser to induce stress at a specific location. This stress riser configuration was used by (Berke and Dallaire, 1994). It is predicted that this reduced depth at the stress riser would simulate actual restraint provided by normal reinforcing bars with settlement effects, autogeneous shrinkage and accelerated evaporation. This geometric configuration has been used by (Qi *et al*., 2003) and proved to be effective.

The second test described by ASTM C1581 uses the restrained ring geometry to study long-term shrinkage of concrete. The ring is assumed to provide infinite restraint. Padron & Zollo (1990) used this type of ring inside a square plate geometry. They placed the specimens inside an environmental chamber to maximize the cracking potential of the specimen.

A narrower panel (500 x 250 x 75mm) with crack inducing risers on the bottom surface was used to study crack potential of high strength concrete by (Sivakumar and Manu, 2007). They also used an environmental chamber during the first 24hrs with regulated temperature, humidity and air velocity to induce faster cracking.

Another variation in geometry is the linear specimens anchored at the ends used by (Banthi *et al*., 1995) with frictionless rollers at the base. This setup, though successful for cement paste, did not produce cracks in concrete specimens.

There are numerous other variations in geometry proposed and used by other researchers. Some of them are;

1. Slab with crack inducing risers (Soroushian & Ravanbakhsh, 1998),

2. Linear specimen with roughened substrate restraint (Banthia, Yan, and Mindess, 1996)

3. Linear specimen with grooved substrate restraint (Naaman, Xia, Hikasa and Saito, 1999).

4. Linear specimen with stress risers and anchored ends (Mora *et al*., 2000)

5. Ring specimen (Weiss and Shah, 2002)

# MATERIALS AND METHODS

## Experimental Program

The experimental program was classified into two series of concrete mixes, M20 and M30. M20 series had 439kg/m$^3$ of cement, and M30 series had 569kg/m$^3$ of concrete. Each series consisted of two types of fibers, steel and PVA, in three volume proportions and a control mix. The study consisted of fourteen mixes in total and details are presented in Appendix Table 1. Preliminary tests were conducted and the mix design was adjusted to obtain a workable mix with cracking before the actual experiments were carried out.

Three major tests were conducted for each batch. They were split tensile test, unrestrained shrinkage test and restrained shrinkage cracking test. In addition, a compressive test with 3 specimens each was done on each series to establish the characteristic strength. The tensile and free shrinkage test had two specimens per batch and the plastic shrinkage cracking test had one specimen per test.

## Materials

1. Cement

Locally available Ordinary Portland cement conforming to ASTM C150 Type I was used throughout the study.

2. Aggregate

Locally available river sand and pea gravel (max. size 9.5mm) were used in the study. The absorption capacity of the fine aggregate was measured to be 1% (ASTM Standard C128, 2007) and the absorption of the coarse aggregate was measured at 0.8% (ASTM Standard C127, 2007) . Both aggregates were tested for moisture content and the mix designs were adjusted accordingly. The material was stored inside the laboratory before use.

3. Fiber
4.
   4.1 DRAMIX RC 65/35-BN Brand Steel fiber

   4.2 KURALON REC 15 x 12 Brand Polyvinyl alcohol (PVA) fiber

**Figure 7** Fibers used in this study, polyvinyl alcohol (L) and steel (R)

**Source:** Manufacturer

5. Clean water
6. Standard cylinder molds Ø6.0 x12.0 inches
7. Prism molds 4.0 x 4.0 x 12 inches for shrinkage test
8. Prism molds with stress risers 4.0 x 4.0 x 24 inches for plastic shrinkage cracking test,
9. Universal testing machine.
10. Crack gauge
11. Length comparator with a dial gauge gradation of 1µm with 200µm range.
12. Standard sieve set
13. Sieve shaker
14. Laboratory Oven
15. Pycnometer
16. Slump cone and rod
17. Concrete mixing machine (Pan mixer & portable mixer)

18. Concrete lab basic tools such as scoop, pans, bowls, etc.
19. Hygrometer
20. Digital scale
21. Photoshop software to analyze the cracks.
22. Computer

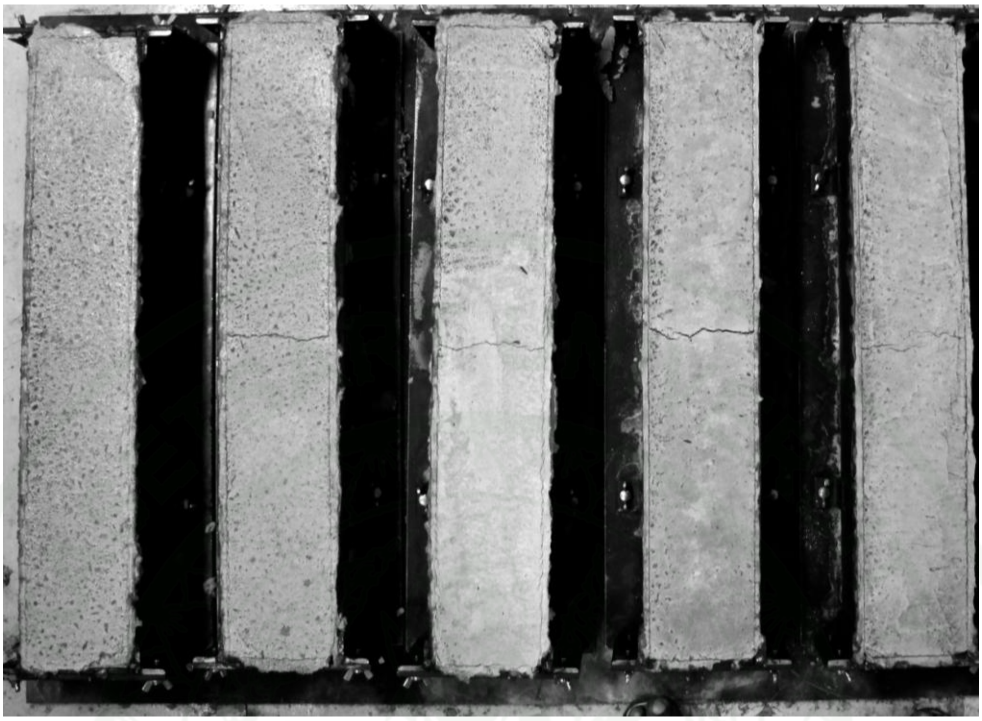


**Figure 8** Restrained shrinkage test specimens

**Figure 9** Restrained shrinkage cracking test setup.

## Methods

### 1. Mix Design

To study and compare the cracking behavior of FRC, it was necessary to produced cracked specimens. Xi *et al*., (2003) showed that increasing the paste volume increased cracking tendency. The mix proportions for this study (given in Appendix Table 2) were designed with high cement content and high water content to induce shrinkage cracking and thus, evaluate the effects of fiber addition. Due to the high water-cement ratio, the concrete workability was adequate, and superplasticizer was not required.

### 2. Specimen Preparation

The specimens were prepared according to the guidelines given in ASTM C192 / C192M - 07, "Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory".

The concrete was mixed in a portable mixer. The dry ingredients were allowed to mix for 1 minute and part of the water was added. After additional 2 minutes the rest of the water was added. The fibers are gradually added as a final ingredient into plain mixed concrete. Then it is mixed further, (average. 3 minutes) until the fibers were evenly distributed throughout the mixture. It was observed that the steel fibers were easy to mix and the PVA fibers tended to bundle up even though the fibers were carefully separated and gradually introduced. PVA fibers were added very slowly to prevent this very effect.

When the concrete was thoroughly mixed, it was placed into the steel molds and external vibration applied. The surface was then screeded and floated with a steel trowel before bleed water started accumulating on the surface. Before placing the concrete all the molds were coated with a thin layer of oil.

## 3. Testing procedures

ACI 544.2R-89, "Measurement of Properties of Fiber Reinforced Concrete" was used as a guideline for all the experiments conducted on FRC.

### 3.1 Fresh Concrete Tests

Slump tests were conducted according to ASTM C143, for each batch. The experiments were conducted in a closed room with an average humidity of 65% and no temperature control. Average temperature during the tests ranged from 32ºC-36ºC at noon.

### 3.1 Compression Test

Compressive strength of concrete was obtained as instructed in ASTM C39. Three 6" x 12" cylinders were cast to test to establish the characteristic strength of each series. The cylinders were broken after 28days and average compressive strength calculated.

### 3.2 Splitting Tensile Test

According to (ACI Committee 544, 1999), results from the splitting tensile test (ASTM C496, 2006) are difficult to interpret because the behavior after the initial crack in unknown and crack initiation is hard to detect.

Standard cylinders of 6-inch diameter were cast and tested by application of incremental loading until they split along the length. The test was carried out on the 28$^{th}$ day and average cracking load from two readings were used to determine the splitting tensile strength of each mix.

3.3 Unrestrained Shrinkage Test

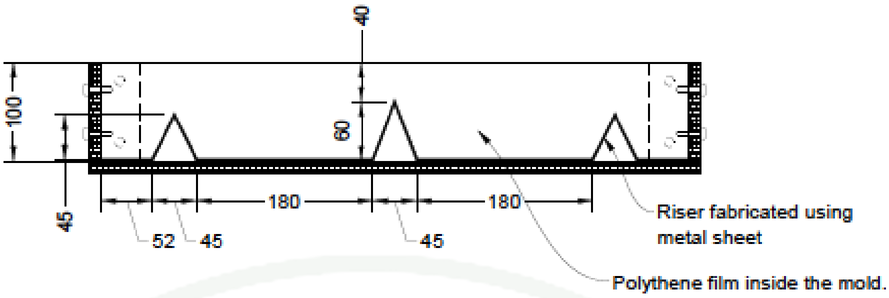
The procedure measures the free shrinkage of concrete specimens described in ASTM C157 and ASTM C341 will be used in this test. These tests are usually conducted simultaneously with the restrained shrinkage tests. In this study, the specimens were stored in a temperature-controlled room to reduce the effect of variation in temperature as much as possible.

Since the size of the specimen had to be greater than 3 inches due to steel fiber length, the modified length change test described in ASTM C341 was used. Two square prisms of size 100mm x 100mm x 319mm were used for each concrete mix with a total of 28 specimens were cast for this test. Specimens were cast and initial length measured after 24hrs. Then the specimens were stored at 25ºC and a length comparator was used to measure the specimens on 1, 2,3, 4, 7 and 14 days. The initial reading was taken as zero value and measurements were taken until the length change over 7-day period is less than 0.001%. The change in length compared to initial length was used to calculate the shrinkage of concrete specimen.

3.4 Restrained Shrinkage Tests

In this study a variation of the test method used by (Berke & Dalliare, 1994), (Soroushian & Ravanbakhsh, 1998) and (Mora *et al.*, 2000) and specified by ASTM C1579 was adopted. Specimens were cast and subjected to accelerated wind velocity using a fan under otherwise normal conditions. After 6 hours the fan was turned off and at 24 hours the initial measurements were taken. This method was chosen to duplicate the field conditions as closely as possible.

The specimens were 100 x 100 x 600mm in size with a crack inducing riser in the middle and two restraints at the ends. The risers reduce the depth of the specimen and provide a junction for stress concentration. This effect is thought to be similar to the stress developed above a reinforcing bar in practice. Figure 10 shows the cross sectional view of the mold used in this test.



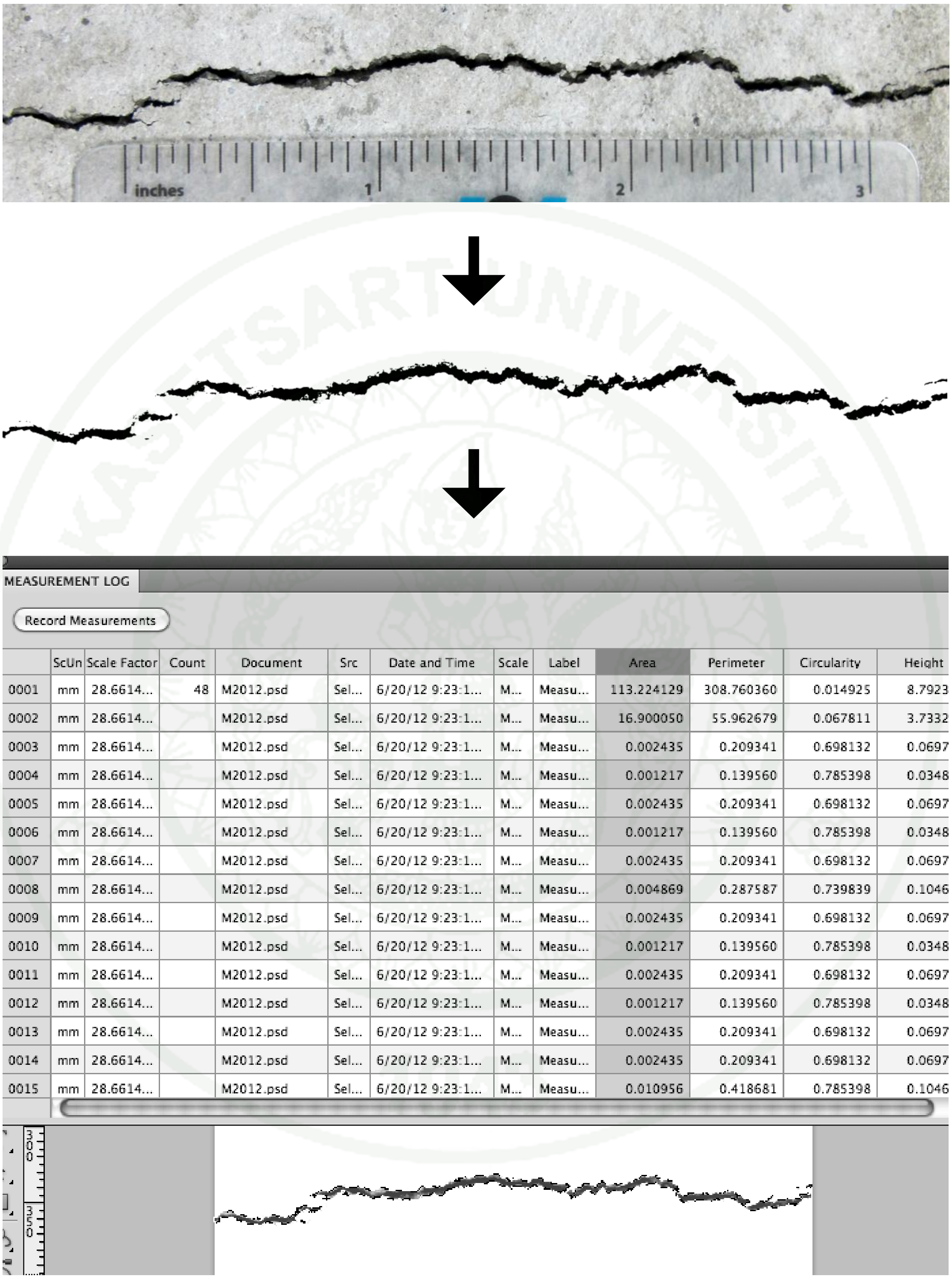

SECTIONAL VIEW

**Figure 10** Restrained shrinkage cracking test mold.

The effect of ambient temperature, relative humidity and wind velocity are well known. Since Bangkok is relatively warm in May and humidity is not extreme (Source: Weather reports), the specimens were cured inside the laboratory with a high velocity fan providing a constant flow of air over the surface of the specimens to provide rapid evaporation.

**4. Crack data acquisition and analysis**

Image analysis was done using semi-automated analysis software for quantifying the cracks. The captured image was processed to remove any lens distortion and a binary image of the crack was extracted. The crack area is masked and measured for each specimen. The image was scaled using the gauge scale captured with the crack and then scaled quantification of the crack was calculated using the software (Figure 11). The results were compared with the control specimen and the area of cracked surface as a percentage of control area was calculated. From this, the reduction of cracks was also calculated.




| | ScUn | Scale Factor | Count | Document | Src | Date and Time | Scale | Label | Area | Perimeter | Circularity | Height |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0001 | mm | 28.6614... | 48 | M2012.psd | Sel... | 6/20/12 9:23:1... | M... | Measu... | 113.224129 | 308.760360 | 0.014925 | 8.7923 |
| 0002 | mm | 28.6614... | | M2012.psd | Sel... | 6/20/12 9:23:1... | M... | Measu... | 16.900050 | 55.962679 | 0.067811 | 3.7332 |
| 0003 | mm | 28.6614... | | M2012.psd | Sel... | 6/20/12 9:23:1... | M... | Measu... | 0.002435 | 0.209341 | 0.698132 | 0.0697 |
| 0004 | mm | 28.6614... | | M2012.psd | Sel... | 6/20/12 9:23:1... | M... | Measu... | 0.001217 | 0.139560 | 0.785398 | 0.0348 |
| 0005 | mm | 28.6614... | | M2012.psd | Sel... | 6/20/12 9:23:1... | M... | Measu... | 0.002435 | 0.209341 | 0.698132 | 0.0697 |
| 0006 | mm | 28.6614... | | M2012.psd | Sel... | 6/20/12 9:23:1... | M... | Measu... | 0.001217 | 0.139560 | 0.785398 | 0.0348 |
| 0007 | mm | 28.6614... | | M2012.psd | Sel... | 6/20/12 9:23:1... | M... | Measu... | 0.002435 | 0.209341 | 0.698132 | 0.0697 |
| 0008 | mm | 28.6614... | | M2012.psd | Sel... | 6/20/12 9:23:1... | M... | Measu... | 0.004869 | 0.287587 | 0.739839 | 0.1046 |
| 0009 | mm | 28.6614... | | M2012.psd | Sel... | 6/20/12 9:23:1... | M... | Measu... | 0.002435 | 0.209341 | 0.698132 | 0.0697 |
| 0010 | mm | 28.6614... | | M2012.psd | Sel... | 6/20/12 9:23:1... | M... | Measu... | 0.001217 | 0.139560 | 0.785398 | 0.0348 |
| 0011 | mm | 28.6614... | | M2012.psd | Sel... | 6/20/12 9:23:1... | M... | Measu... | 0.002435 | 0.209341 | 0.698132 | 0.0697 |
| 0012 | mm | 28.6614... | | M2012.psd | Sel... | 6/20/12 9:23:1... | M... | Measu... | 0.001217 | 0.139560 | 0.785398 | 0.0348 |
| 0013 | mm | 28.6614... | | M2012.psd | Sel... | 6/20/12 9:23:1... | M... | Measu... | 0.002435 | 0.209341 | 0.698132 | 0.0697 |
| 0014 | mm | 28.6614... | | M2012.psd | Sel... | 6/20/12 9:23:1... | M... | Measu... | 0.002435 | 0.209341 | 0.698132 | 0.0697 |
| 0015 | mm | 28.6614... | | M2012.psd | Sel... | 6/20/12 9:23:1... | M... | Measu... | 0.010956 | 0.418681 | 0.785398 | 0.1046 |

**Figure 11** Crack data analysis procedure

# RESULTS AND DISCUSSION

## 1. Fresh concrete

The workability of concrete declined with increase in fiber volume. It was observed that slump decreased considerably for the M30 series (refer to Appendix Table 2), with higher cement content, than the M20 series. Even though the fiber content used in this study was considerably low at less than 2% for all mixtures, bunching of PVA fibers was observed.

Figure 12 below shows a comparison of slump decline for both series. The M30 series with higher cement content had the lowest slump. Slump declined proportionally with increase in fiber volume and steel fiber had the least effect on the slump.

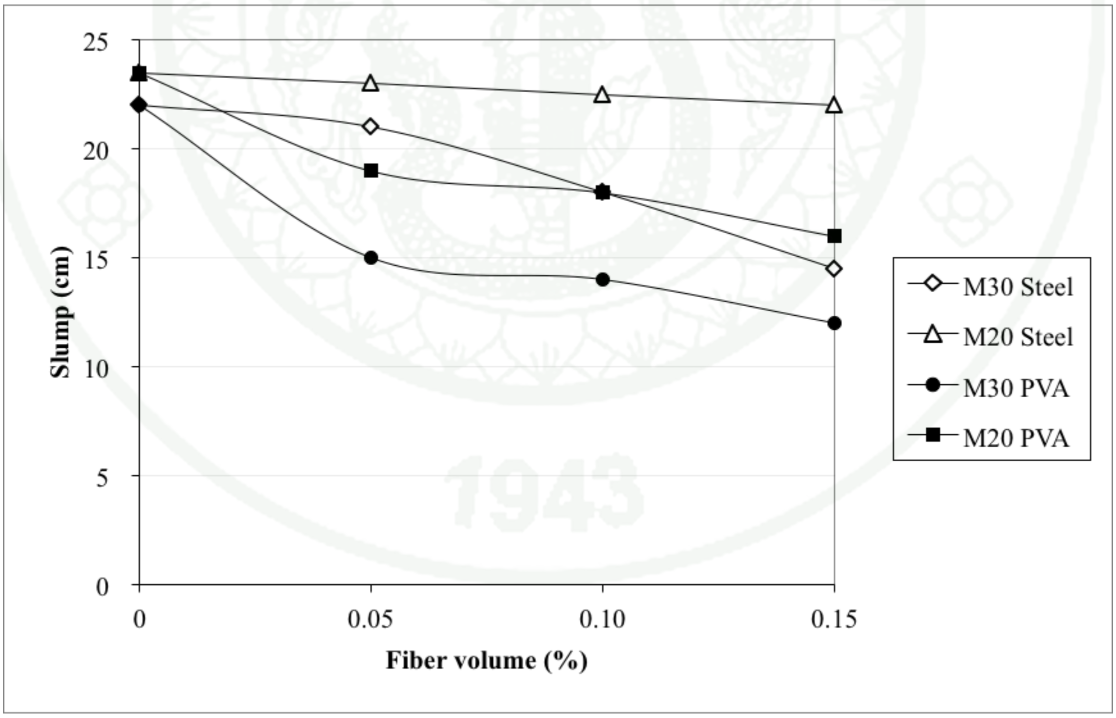



**Figure 12** Effect of fiber content on slump for Series M20 and M30.

## 2. Plastic Shrinkage Cracking

Total crack area was calculated for each specimen using image analysis software. All 14 specimens used for this test showed cracks within the first 5 hours and no new cracks were observed during the next 7 days.

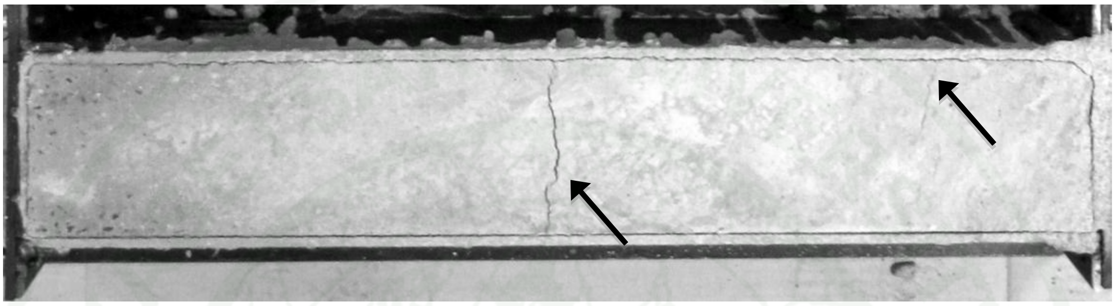


**Figure 13** Typical cracked specimens

Figure 13 shows the typical crack pattern observed for all specimens Cracks appeared perpendicular to the length of the specimen and direction of screeding. They were located in the center of the specimen directly above the stress riser and extended fully across the specimen. Some specimens had secondary hairline cracks above the restraint risers; they did not fully extend across the surface of the prism. Hairline cracks that occurred only at one end were not typical, but present this particular specimen.

Since both mixes had high water content and only one had high cement content it was expected that both series would have similar cracking behavior. This is seen to some extent in the control specimen and low volume steel fiber concrete specimens. In every other mix, the cracking was significantly lower for low strength series, M20. The effect of paste may have been countered by the additional tensile strength of the concrete due to the fibers present in the matrix. These effects can clearly be seen in the crack comparison images (Figure 28-31).

From the crack area calculations it was observed that the specimens with PVA fibers were most effective at crack reduction. Figure 14 shows that, at 0.05% fiber content, FRC specimens had average reduction of 24% plastic cracks while the PVA specimens had a significantly higher average reduction of 55%. At 0.1% fiber content, the steel fiber concrete had 35% reduction and the PVA fiber specimens averaged 64%. At the maximum fiber content used. 0.15% fiber volume, steel fiber reduced 31% cracks and PVA fibers reduced 79% cracks. These estimates are averaged for both series of concrete used in this study. This significance of PVA microfibers could be explained by their shorter size and diameter compared with the steel fibers used in this study (Qi *et al*., 2005 and Banthia *et al.*, 1996).

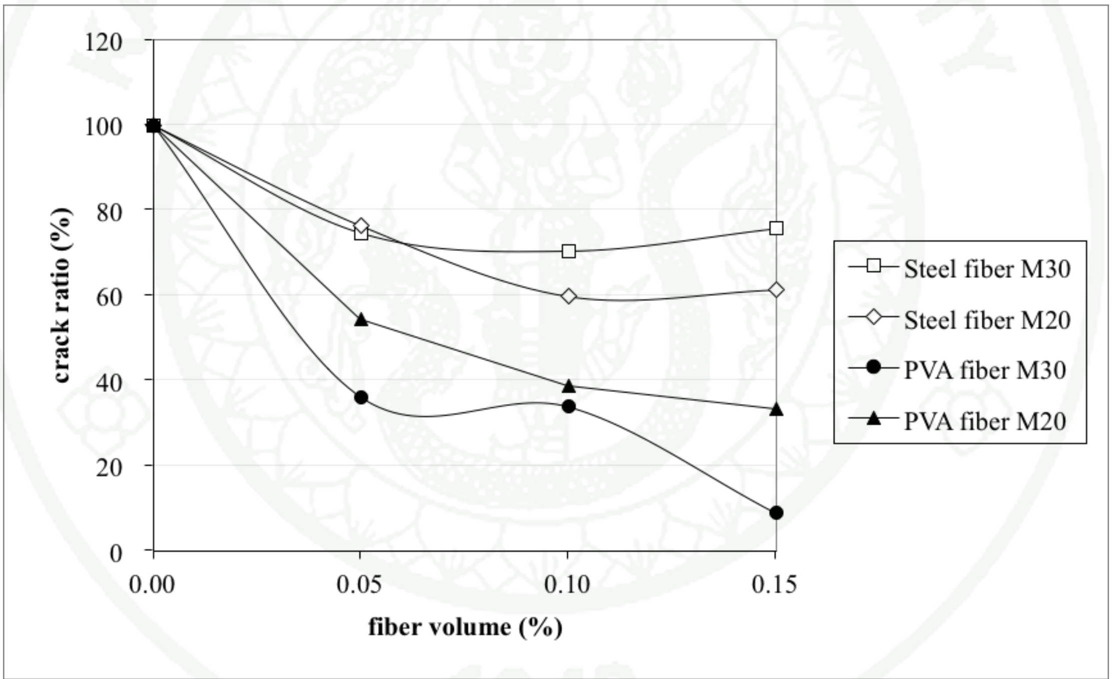



**Figure 14** Effect of fiber content on total plastic shrinkage cracking area (in mm2) observed for concrete series M20 and M30

When the crack reduction behavior of steel fiber was considered (in Figure 15) for both series, total crack area of steel fiber concrete was less than that of plain concrete. The reduction increased with increase in fiber volume and this effect is expected to be significant with higher steel fiber volume as seen by Jozsa & Fenveysi,

(2010) and Eren & Marar, (2010). The highest reduction observed was with 40% and 30% with 0.1% fiber volume for M20 and M30 respectively. For concrete with 0.05% fiber volume, the crack reduction percentage was 24% and 25% and up to 0.05% fiber volume the low strength M20 series had higher crack area. Between 0.05% and 0.1% fiber volume this effect reversed and M30 series showed higher total crack area. At 0.15% the crack reduction percentage was lower that of 0.1% for both concrete mixes. For both series of concrete the trend line showed a shallow linear decline with increase in steel fiber volume.

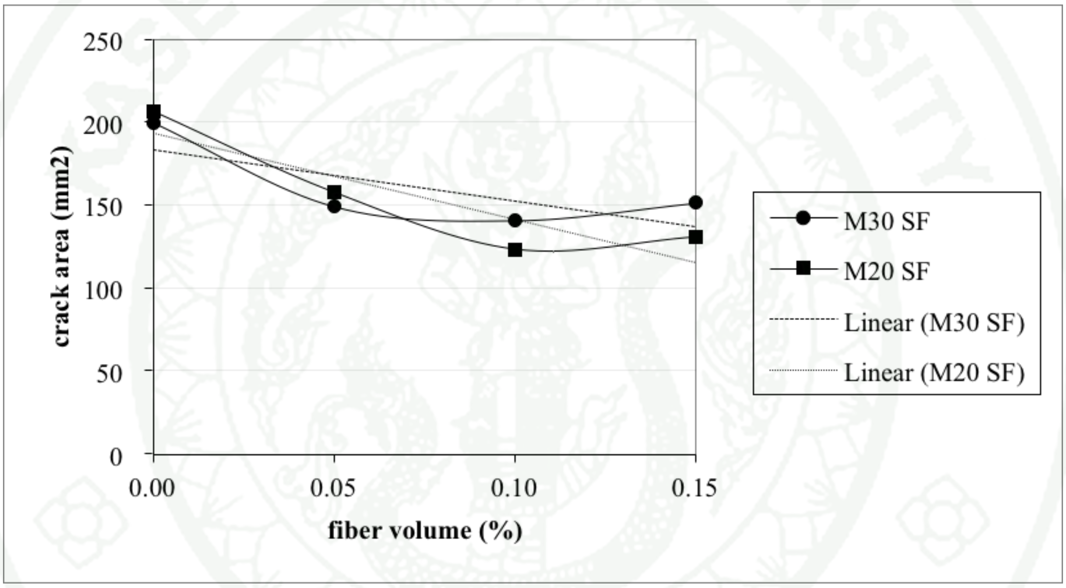



**Figure 15** Effect of steel fiber volume on total plastic shrinkage cracking area (in mm2) observed for concrete series M20 and M30

When the crack reduction behavior of PVA fiber was considered for both series (Figure 16), a very significant reduction in total cracked area was observed. M30 series showed the highest improvement, with 91% reduction for 0.15% fiber volume, 66% with 0.1% and 64% with 0.05% fiber volume. With 0.15% fiber volume in M20, 66% of the cracks were controlled and 61% of the cracks were controlled with 0.1% fiber volume. However, for 0.05% fiber volume with 24% cracks reduction. From these results it can be determined that a near total elimination of all visible cracks could be possible with a slightly higher volume of PVA fibers. Figure

17 shows the curve for both concrete series and the trend line, which shows a steep decline. At 0.1% the data varied slightly. This can be ignored in favor of the general trend.

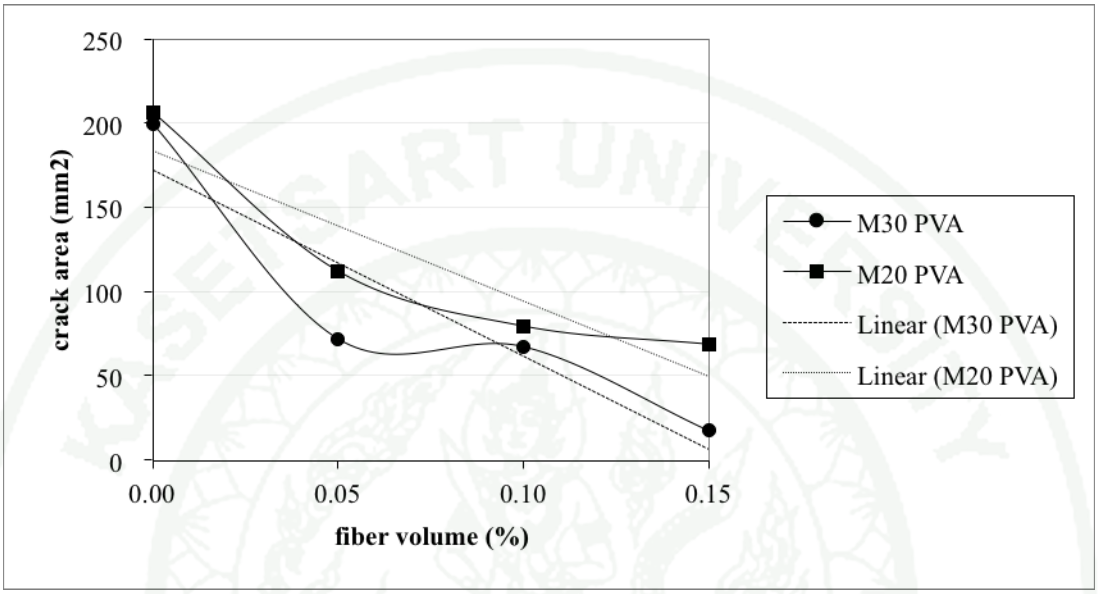



**Figure 16** Effect of PVA fiber volumes on total plastic shrinkage cracking area (in mm2) observed for concrete series M20 and M30

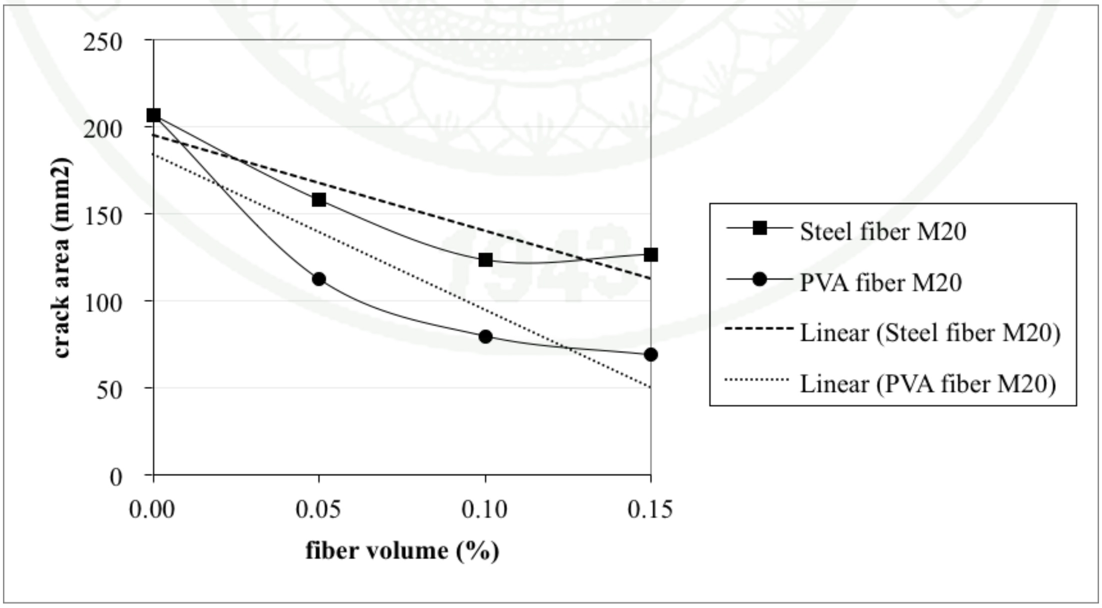



**Figure 17** Effect of fiber type on total plastic shrinkage crack area for series M20

Comparison between fiber types for both mixtures (Figure 17 and 18), show asteep decline in cracking area was observed for PVA. These observations are similar to the findings of Xiao *et al.*, (2011).

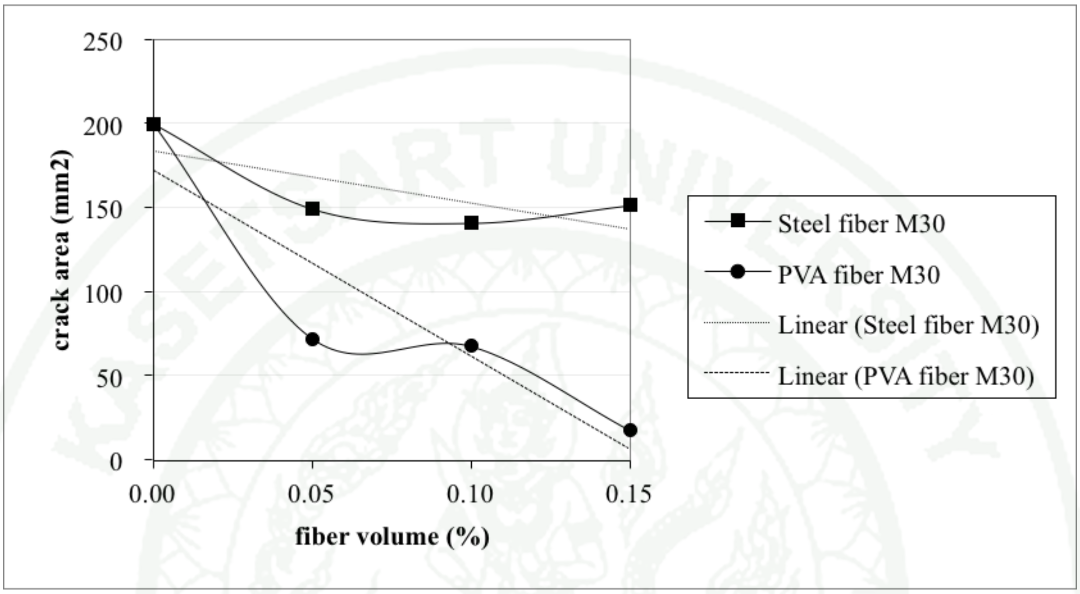



**Figure 18** Effect of fiber type on total plastic shrinkage crack area for series M30

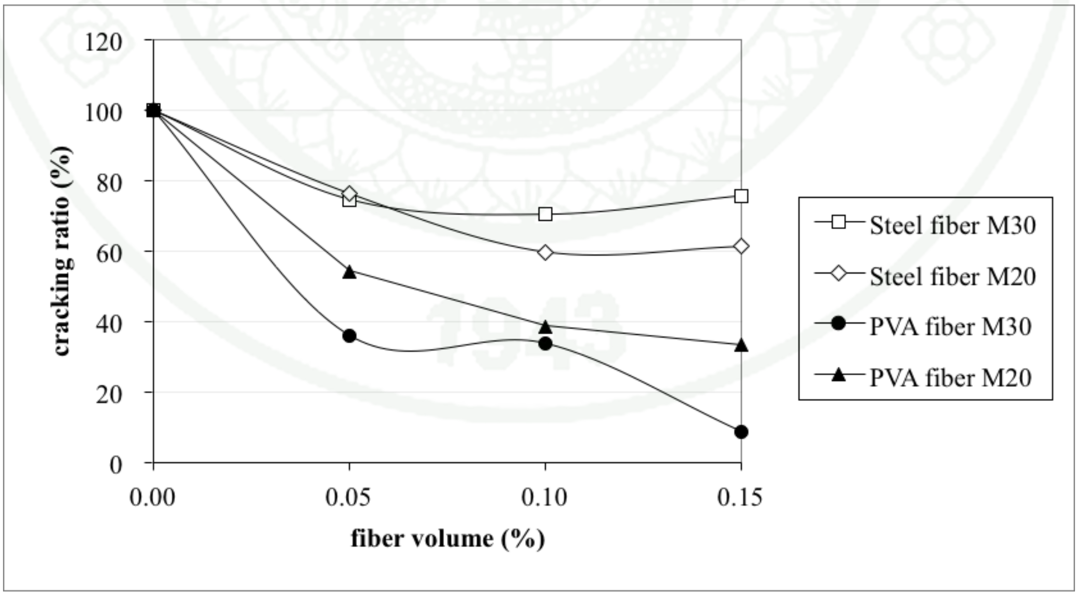



**Figure 19** Cracking ratio of all the fiber reinforced mixtures compared with normal concrete

### 3. Free Shrinkage Test

Free shrinkage measurements for unrestrained specimens, dry-cured under controlled environmental conditions are presented in Appendix Table 10 and 11.

The shrinkage curves plotted from the tables (in Figure 20) shows the shrinkage for M20 series of specimens. The control specimen had the highest shrinkage as expected. PVA and steel FRC with the lowest fiber content (PVA1 and SF1) did not shown any significant shrinkage compared to plain concrete. The PVA3 mix with 0.15% fiber had the least shrinkage. In all the mixes it was observed that with increase in fiber volume, shrinkage increased rapidly for the first 2-3 days and declined within two weeks. This rapid rate of shrinkage during the first 2 days can be attributed to the combined effect of drying and chemical (autogenous shrinkage) and plastic shrinkage. The behavior tallies with the results obtained by (Altoubat & Lange, 2002).

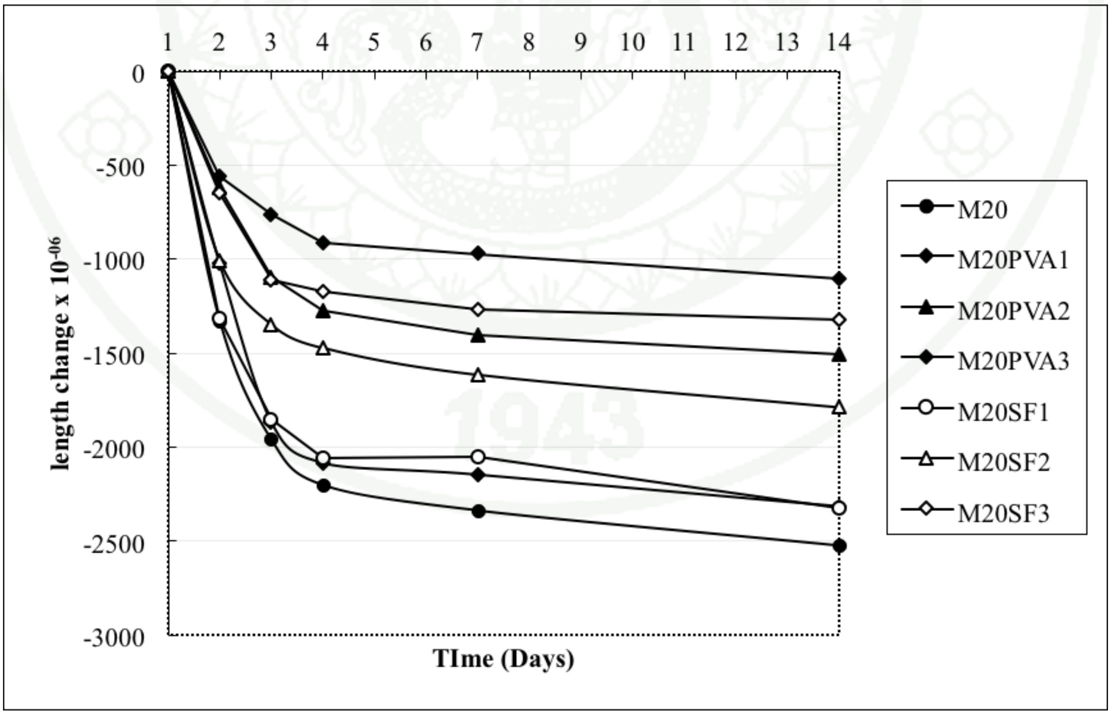



**Figure 20** Free shrinkage of M20 concrete series over 14 days

Analyzing the shrinkage behavior by comparison with control specimen, PVA1 and SF1 mixtures showed 8.3% and 7.8% difference in shrinkage, respectively. PVA2 mixture showed a 40% reduction while SF2 had just 29%. PVA3 and SF3 with the highest fiber content of 0.15% fiber showed a reduction with 56% and 48% respectively. From these results it can be determined that at 0.05% neither PVA nor steel fibers had any desirable impact, but at 0.15% the control of shrinkage was significant enough at nearly 50% for both types of fibers.

M30 series, with higher cement content had comparatively less shrinkage compared to M20 series. The minimum fiber volume at 0.1% showed less than 9% shrinkage for both steel and PVA fibers. Even in this series, PVA3 with 0.15% fiber volume, had the least shrinkage with 45% reduction while 0.1% PVA2 had 26% reduction. Steel fiber specimens with 0.1% fiber content had 30% reduction but 0.15% fiber specimens showed a dubious result with just 22% reduction. This value could be an error and ignored. All the specimens showed a rapid shortening during the first 3 days, which sloped into a slow decline with time (Figure 21).

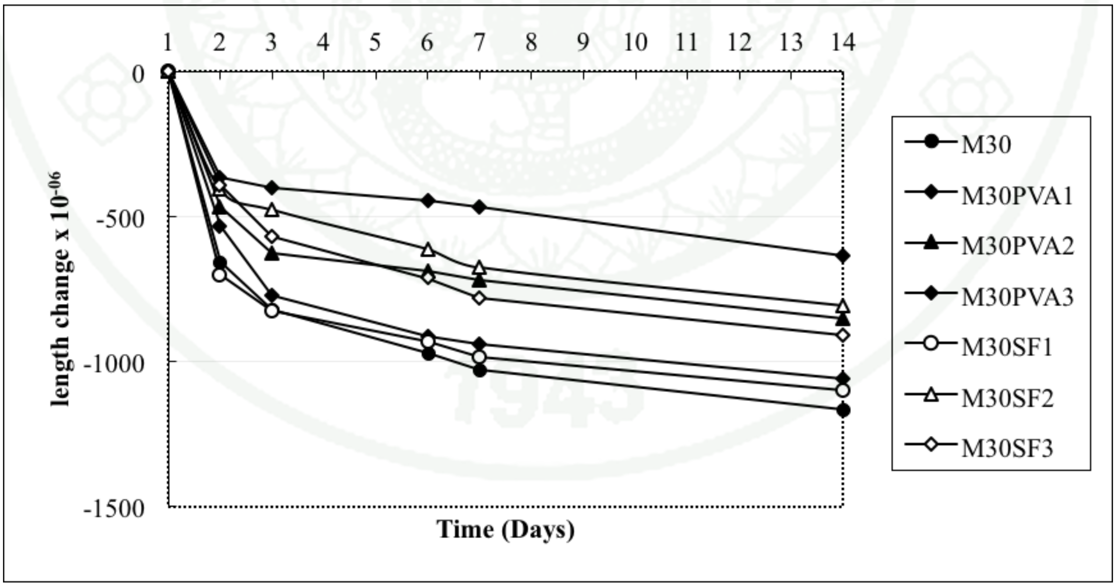



**Figure 21** Free shrinkage of M30 concrete series with over 14 days.

**4. Splitting Tensile Test**

Tensile strength tests showed that low volume fiber content did not increase the tensile capacity of concrete (Appendix table 12). Strength curves for steel showed a very slight improvement, which must be concluded, as inconclusive because the initial cracking load of the test specimen was difficult to determine. This effect was expected and corroborated by Myers, (2006) and ACI Committee 544, (1999).

At ultimate tensile load both the plain concrete and PVA fiber specimens split completely from the middle. The PVA fibers were short with very low modulus of elasticity and they could not add any additional tensile capacity to the concrete All the PVA FRC cylinders split apart completely at ultimate load. But in steel FRC specimens, even after initial cracking, the steel fibers could carry additional load due to their high elastic modules. It was also observed that none of the steel fiber cylinders broke apart at ultimate load (Figure 32).

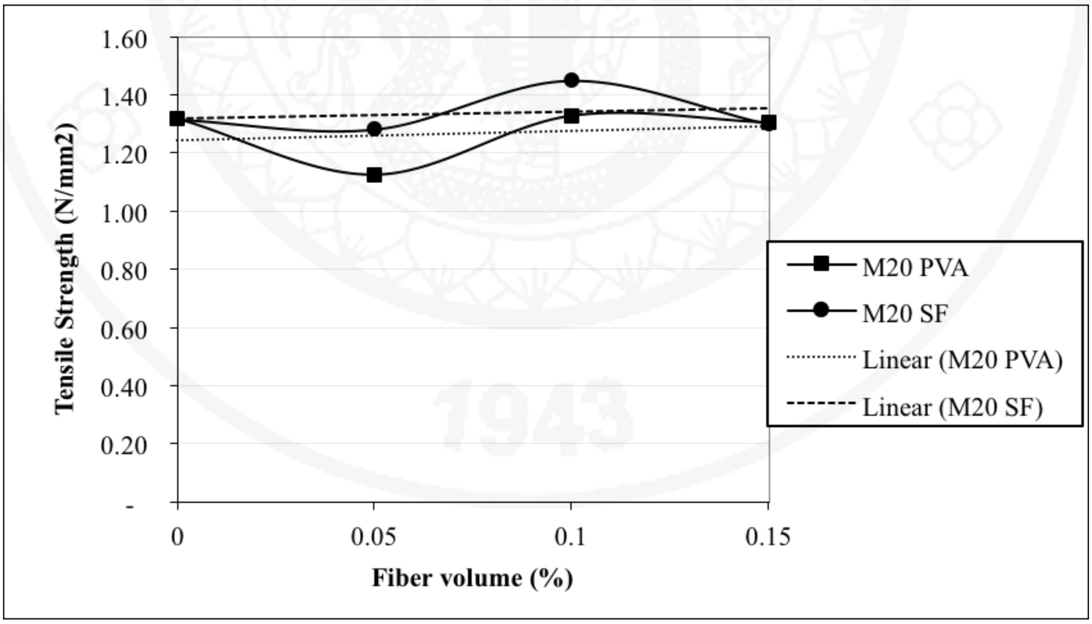



**Figure 22** Splitting tensile strength of M20 concrete series for steel and PVA fiber at 28 days.

Tensile capacity of M30 series was 20% higher than that of M20 series. Even in this series, at 0.05% fiber content the tensile strength was less than that of control mixtures for both types of fibers. However, for 0.1% and 0.15% fiber, strength increased linearly. This effect is not significant because the overall strength curve for both fiber types did not show any significant improvement. Therefore it can be concluded that low fiber volumes do not improve the tensile strength of cement rich mixtures either.

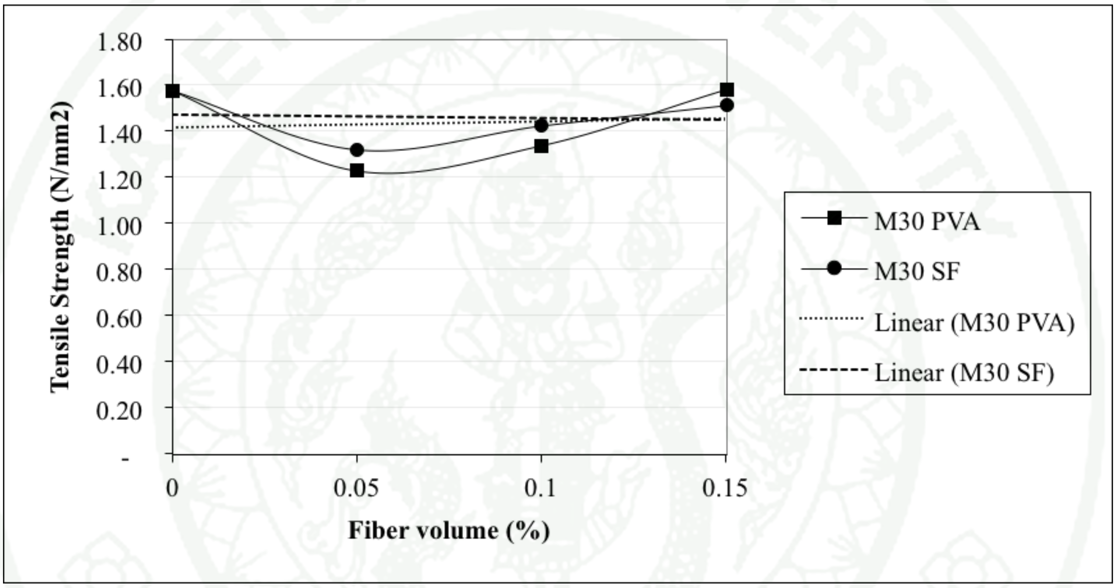



**Figure 23** Splitting tensile strength of M30 concrete series for steel and PVA fiber at 28 days.

It can be concluded that splitting tensile tests did no show improvement in the ultimate tensile capacity, but the fibers slowed the cracking to some extent. For all mixtures the steel fiber specimens performed better than PVA fiber specimens, which could be due to the huge difference in modulus of elasticity of the two fibers themselves. The lack of improvement in strength may be due to the low strength of the concrete mix (which was deliberately kept low to induce cracking) and the difference in failure mechanism of the fibers and bonding behavior (Lawler *et al.*, 2005).

# CONCLUSION AND RECOMMENDATIONS

## Conclusion

This study presents the results of studies performed to determine the effect of steel and PVA fiber content (0.05%-0.15%) on the plastic shrinkage cracking behavior of FRC. Comparison was made with plain concrete using restrained shrinkage tests and free shrinkage tests as well as splitting tensile tests. Based on the tests results, the following conclusions can be drawn:

1. As the fiber volume increases there is a marked reduction in plastic cracking, this is most significant for PVA fiber at 0.15% volume with greater than 60% reduction for all mixtures. PVA fiber is very effective at low volumes for plastic crack reduction of normal strength concretes. For steel fiber mixtures the average reduction was less than 30% and taking into account the cost of FRC, this improvement is not significant enough at this volume range.

2. Both PVA and steel fiber showed a very slight decrease in free shrinkage, but this behavior is not consistent for both every concrete mix

3. At low volume, steel fiber does not reduce workability, but PVA fiber reduced slump and workability. It was extremely difficult to mix higher volume of PVA fiber thoroughly

5. No improvement in the splitting tensile strength of concrete was observed with addition of fibers.

## Recommendations

The influence of steel fiber and PVA fiber at very low volume was studied. This study was conducted with just two fiber types. Further research options warranted to study the subject are:

1. Study the effect of PVA fiber on shrinkage cracking with higher fiber volume and different geometric shapes and aspect ratios.

2. Study the tensile strength variation with different types of fibers with focus on moderate fiber volumes and long-term shrinkage.

3. Study the bond characteristics and tensile strength relationship of FRC in relation to different fibers and compare with the shrinkage effects.

4. Higher strength concrete with low volume fibers should be checked to see if plastic shrinkage cracks could be similarly reduced.

Due to circumstances it was not possible to study these aspects in this research project, but the above factors are important to establish a through understanding

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# APPENDIX

**Appendix Table 1** Detail of experimental program.

| Series | Mix Designation | Water/cement ratio | Fiber content ($kg/m^3$) | Fiber length (mm) | Aspect ratio |
|---|---|---|---|---|---|
| | M20 | 0.63 | - | - | - |
| | M20PVA1 | 0.63 | 0.655 | 12 | 45 |
| | M20PVA2 | 0.63 | 1.310 | 12 | 45 |
| M20 | M20PVA3 | 0.63 | 1.965 | 12 | 45 |
| | M20SF1 | 0.63 | 3.925 | 35 | 64 |
| | M20SF2 | 0.63 | 7.850 | 35 | 64 |
| | M20SF3 | 0.63 | 11.775 | 35 | 64 |
| | M30 | 0.49 | - | - | - |
| | M30PVA1 | 0.49 | 0.655 | 12 | 45 |
| | M30PVA2 | 0.49 | 1.310 | 12 | 45 |
| M30 | M30PVA3 | 0.49 | 1.965 | 12 | 45 |
| | M30SF1 | 0.49 | 3.925 | 35 | 64 |
| | M30SF2 | 0.49 | 7.850 | 35 | 64 |
| | M30SF3 | 0.49 | 11.775 | 35 | 64 |

**Appendix Table 2** Concrete mix proportions

| Designation | Cement ($kg/m^3$) | Fine Aggregate ($kg/m^3$) | Coarse Aggregate ($kg/m^3$) | Water ($kg/m^3$) |
|---|---|---|---|---|
| M20 | 439.00 | 822.12 | 690.62 | 277.02 |
| M30 | 569.00 | 717.32 | 690.62 | 276.41 |

**Appendix Table 3** Properties of fibers used in the study

| Type of Fiber | Geometry | Diameter | Length (mm) | Specific Gravity | Tensile Strength ($N/mm^2$) | Elastic Modulus ($KN/mm^2$) |
|---|---|---|---|---|---|---|
| Steel | Monofilament | 0.55mm | 35 | 7.85 | 1160 | 210 |
| PVA | Monofilament | 40µm | 12 | 1.3 | 1600 | 40 |

**Appendix Table 4** Detail of Coarse aggregate tests

| Description | 1 | 2 | 3 |
|---|---|---|---|
| Oven Dry weight (A) | 2157.46 | ~~2171.9~~ | 2925.43 |
| Weight SSD sample (B) | 2176.1 | ~~2382.3~~ | 2947.55 |
| Weight of sample in water (C) | 1427.1 | ~~1515.5~~ | |
| Absorption =B-A/A% | 0.864 | ~~9.687~~ | 0.756 |
| Absorption % | | 0.81 | |
| (BSG) = A/B-C | 2.88 | 2.506 | |
| Bulk Specific Gravity | | 2.69 | |
| BSG $_{SSD}$ = B/B-C | 2.905 | 2.748 | |
| BSG $_{SSD}$ = | | 2.83 | |
| $G_{sa}$ = A/A-C | 2.954 | 3.309 | |
| Apparent Specific Gravity = | | 3.13 | |

**Appendix Table 5** Detail of fine aggregate tests

| Description | 1 | 2 | 3 |
|---|---|---|---|
| Oven Dry Weight (A) | 495.27 | 495.42 | 860.82 |
| Weight of Water + flask (B) | 897.17 | 897.17 | |
| Weight of sample in water( C) | 1201.44 | 1201.59 | |
| SSD Sample weight (S) | 499.955 | 500.04 | 869.1 |
| Absorption =B-A/A% | 0.946 | 0.933 | 0.962 |
| Absorption % | | 0.95 | |
| (BSG) = A/B-C | 2.531 | 2.533 | |
| BSG | | 2.53 | |
| BSG $_{SSD}$ = B/B-C | 2.555 | 2.556 | |
| BSG $_{SSD}$ = | | 2.56 | |
| $G_{sa}$ = A/A-C | 2.593 | 2.594 | |
| Apparent Specific Gravity = | | 2.59 | |

**Appendix Table 6** Test for Moisture Content of aggregates

| Description | Fine Aggregate (grams) | Coarse Aggregate (grams) |
|---|---|---|
| Air Dry (A) | 1248.19 | 2452.15 |
| Oven Dry (B) | 1243.59 | 2449.96 |
| Absorption =B-A/A% | 0.37 | 0.09 |

**Appendix Table 7** Sieve analysis of fine aggregates

| Sieve Size | Retained Weight (g) | % Retained | Cumulative % Retained | Weight Retained (g) | % Retained | Cumulative % Retained |
|---|---|---|---|---|---|---|
| 6.3mm | 0 | 0 | 0 | 0 | 0 | 0 |
| 4.75mm | 16.11 | 3 | 3 | 17.15 | 3 | 3 |
| 2.36mm | 57.27 | 11 | 14 | 73.65 | 15 | 18 |
| 1.18mm | 75.54 | 15 | 29 | 88.43 | 18 | 36 |
| 600µm | 107.08 | 21 | 50 | 105.02 | 21 | 57 |
| 300µm | 142.77 | 29 | 79 | 140.01 | 28 | 85 |
| 150µm | 72.54 | 14 | 93 | 46.7 | 9 | 94 |
| 75µm | 0 | 0 | 93 | 0 | 0 | 94 |
| Pan | 18.79 | 4 | 97 | 18.81 | 4 | 98 |
| Total | 490.1 | 97 | | 489.77 | 98 | |
| Fineness Modulus | | | 2.805 | | | |

**Appendix Table 8** Results of slump test for series M20 and M30.

| Fiber Type | Mix Designation | Fiber Volume (%) | Slump (cm.) | |
|---|---|---|---|---|
| | | | Series M20 | Series M30 |
| Control | M20 | 0.00 | 23.5 | 22.0 |
| PVA | M20PVA1 | 0.05 | 19 | 15 |
| | M20PVA2 | 0.15 | 18 | 14 |
| | M20PVA3 | 0.20 | 16 | 12 |
| Steel | M20SF1 | 0.05 | 23.5 | 21 |
| | M20SF2 | 0.15 | 22.5 | 18 |
| | M20SF3 | 0.20 | 22 | 14.5 |

**Appendix Table 9** Results of plastic shrinkage cracking test at 24hrs.

| Series | Fiber Content (Vol. %) | Crack Area (in mm.$^2$) | |
|---|---|---|---|
| | | M20 | M30 |
| Control | - | 206.72 | 200.12 |
| PVA | 0.05 | 112.41 | 72.39 |
| | 0.10 | 79.87 | 96.52 |
| | 0.15 | 69.14 | 17.81 |
| Steel | 0.05 | 157.94 | 151.78 |
| | 0.10 | 231.86 | 153.44 |
| | 0.15 | 131.14 | 143.25 |

**Appendix Table 10** Summary of free shrinkage rest results for M20 series (in µm.).

| Day | Control | PVA Fiber | | | Steel Fiber | | |
|---|---|---|---|---|---|---|---|
| | | PVA1 | PVA2 | PVA3 | SF1 | SF2 | SF3 |
| 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2 | 1327 | 1026 | 623 | 562 | 1318 | 1007 | 693 |
| 3 | 1960 | 1867 | 1095 | 765 | 1853 | 1348 | 1113 |
| 4 | 2201 | 2083 | 1273 | 912 | 2057 | 1473 | 1169 |
| 7 | 2337 | 2147 | 1405 | 972 | 2055 | 1616 | 1268 |
| 14 | 2523 | 2315 | 1507 | 1107 | 2327 | 1789 | 1326 |

**Appendix Table 11** Summary of free shrinkage rest results for M30 series in (in µm.)

| Day | Control | PVA Fiber | | | Steel Fiber | | |
|---|---|---|---|---|---|---|---|
| | | PVA1 | PVA2 | PVA3 | SF1 | SF2 | SF3 |
| 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2 | 417 | 493 | 581 | 265 | 209 | 690 | 345 |
| 3 | 600 | 882 | 687 | 322 | 422 | 1078 | 397 |
| 4 | 744 | 1074 | 649 | 360 | 505 | 1239 | 487 |
| 7 | 806 | 1211 | 685 | 358 | 552 | 1356 | 529 |
| 14 | 1069 | 1464 | 853 | 543 | 633 | 1730 | 790 |

**Appendix Table 12** Summary of splitting tensile test rest results after 28 days (in $N/mm^2$).

| Fiber Type | Mix Designation | Fiber Volume (%) | Tensile Strength ($N/mm^2$) | |
|---|---|---|---|---|
| | | | Series M20 | Series M30 |
| Control | M20 | 0.00 | 1.314 | 1.578 |
| PVA | M20PVA1 | 0.05 | 1.121 | 1.231 |
| | M20PVA2 | 0.15 | 1.324 | 1.341 |
| | M20PVA3 | 0.20 | 1.301 | 1.585 |
| Steel | M20SF1 | 0.05 | 1.280 | 1.322 |
| | M20SF2 | 0.15 | 1.447 | 1.426 |
| | M20SF3 | 0.20 | 1.298 | 1.514 |

**Appendix Table 13** Crack area calculation for control specimen, M20 series

| # | Scale Units | Scale Factor | Area | Perimeter | Circularity | Height | Width |
|---|---|---|---|---|---|---|---|
| 1 | mm | 27.8 | 103.36 | 291.60 | 0.02 | 11.51 | 96.37 |
| 2 | mm | 27.8 | 0.00 | 0.22 | 0.70 | 0.04 | 0.07 |
| 3 | mm | 27.8 | 12.06 | 33.19 | 0.14 | 2.99 | 12.88 |
| 4 | mm | 27.8 | 0.00 | 0.14 | 0.79 | 0.04 | 0.04 |
| 5 | mm | 27.8 | 0.00 | 0.14 | 0.79 | 0.04 | 0.04 |
| 6 | mm | 27.8 | 0.00 | 0.14 | 0.79 | 0.04 | 0.04 |
| 7 | mm | 27.8 | 1.15 | 9.55 | 0.16 | 1.01 | 3.78 |
| 8 | mm | 27.8 | 0.00 | 0.14 | 0.79 | 0.04 | 0.04 |
| 9 | mm | 27.8 | 31.65 | 86.60 | 0.05 | 4.39 | 30.14 |
| 10 | mm | 27.8 | 0.00 | 0.14 | 0.79 | 0.04 | 0.04 |
| 11 | mm | 27.8 | 0.00 | 0.26 | 0.74 | 0.07 | 0.07 |
| 12 | mm | 27.8 | 0.01 | 0.52 | 0.54 | 0.07 | 0.22 |
| 13 | mm | 27.8 | 0.00 | 0.14 | 0.79 | 0.04 | 0.04 |
| 14 | mm | 27.8 | 0.00 | 0.14 | 0.79 | 0.04 | 0.04 |
| 15 | mm | 27.8 | 0.00 | 0.14 | 0.79 | 0.04 | 0.04 |
| 16 | mm | 27.8 | 0.00 | 0.22 | 0.70 | 0.04 | 0.07 |
| 17 | mm | 27.8 | 0.00 | 0.14 | 0.79 | 0.04 | 0.04 |
| 18 | mm | 27.8 | 0.00 | 0.14 | 0.79 | 0.04 | 0.04 |
| 19 | mm | 27.8 | 0.00 | 0.22 | 0.70 | 0.07 | 0.04 |
| 20 | mm | 27.8 | 0.01 | 0.39 | 0.76 | 0.11 | 0.14 |
| 21 | mm | 27.8 | 0.00 | 0.14 | 0.79 | 0.04 | 0.04 |
| 22 | mm | 27.8 | 0.00 | 0.14 | 0.79 | 0.04 | 0.04 |
| 23 | mm | 27.8 | 42.55 | 99.85 | 0.05 | 4.10 | 39.06 |
| 24 | mm | 27.8 | 0.00 | 0.14 | 0.79 | 0.04 | 0.04 |
| 25 | mm | 27.8 | 0.00 | 0.14 | 0.79 | 0.04 | 0.04 |

**Appendix Table 13** (Continued)

| # | Scale Units | Scale Factor | Area | Perimeter | Circularity | Height | Width |
|---|---|---|---|---|---|---|---|
| 26 | mm | 27.8 | 0.00 | 0.22 | 0.70 | 0.07 | 0.04 |
| 27 | mm | 27.8 | 0.00 | 0.14 | 0.79 | 0.04 | 0.04 |
| 28 | mm | 27.8 | 0.00 | 0.22 | 0.70 | 0.04 | 0.07 |
| 29 | mm | 27.8 | 0.00 | 0.14 | 0.79 | 0.04 | 0.04 |
| 30 | mm | 27.8 | 15.67 | 52.89 | 0.07 | 3.13 | 18.38 |
| 31 | mm | 27.8 | 0.00 | 0.14 | 0.79 | 0.04 | 0.04 |
| 32 | mm | 27.8 | 0.01 | 0.35 | 0.67 | 0.11 | 0.11 |
| 33 | mm | 27.8 | 0.00 | 0.22 | 0.70 | 0.07 | 0.04 |
| 34 | mm | 27.8 | 0.00 | 0.14 | 0.79 | 0.04 | 0.04 |
| 35 | mm | 27.8 | 0.00 | 0.14 | 0.79 | 0.04 | 0.04 |
| 36 | mm | 27.8 | 0.00 | 0.14 | 0.79 | 0.04 | 0.04 |
| 37 | mm | 27.8 | 0.00 | 0.14 | 0.79 | 0.04 | 0.04 |
| 38 | mm | 27.8 | 0.01 | 0.30 | 0.74 | 0.07 | 0.11 |
| 39 | mm | 27.8 | 0.01 | 0.60 | 0.45 | 0.14 | 0.22 |
| 40 | mm | 27.8 | 0.00 | 0.14 | 0.79 | 0.04 | 0.04 |
| 41 | mm | 27.8 | 0.00 | 0.14 | 0.79 | 0.04 | 0.04 |
| 42 | mm | 27.8 | 0.00 | 0.14 | 0.79 | 0.04 | 0.04 |
| 43 | mm | 27.8 | 0.17 | 2.21 | 0.45 | 0.54 | 0.68 |
| 44 | mm | 27.8 | 0.00 | 0.14 | 0.79 | 0.04 | 0.04 |
| Total Area | | 206.72 | | | | | |

**Appendix Table 14** Crack area calculation for specimen M20PVA1

| # | Scale Units | Scale Factor | Area | Perimeter | Circularity | Height | Width |
|---|---|---|---|---|---|---|---|
| 1 | mm | 26.20 | 56.21 | 323.39 | 0.01 | 11.49 | 97.25 |
| 2 | mm | 26.20 | 18.77 | 93.81 | 0.03 | 11.49 | 24.81 |
| 3 | mm | 26.20 | 0.00 | 0.15 | 0.79 | 0.04 | 0.04 |
| 4 | mm | 26.20 | 0.00 | 0.15 | 0.79 | 0.04 | 0.04 |
| 5 | mm | 26.20 | 0.01 | 0.49 | 0.53 | 0.11 | 0.15 |
| 6 | mm | 26.20 | 0.00 | 0.31 | 0.59 | 0.11 | 0.04 |
| 7 | mm | 26.20 | 0.00 | 0.27 | 0.74 | 0.08 | 0.08 |
| 8 | mm | 26.20 | 0.00 | 0.27 | 0.74 | 0.08 | 0.08 |
| 9 | mm | 26.20 | 0.00 | 0.23 | 0.70 | 0.04 | 0.08 |
| 10 | mm | 26.20 | 0.00 | 0.15 | 0.79 | 0.04 | 0.04 |
| 11 | mm | 26.20 | 0.00 | 0.15 | 0.79 | 0.04 | 0.04 |
| 12 | mm | 26.20 | 0.00 | 0.15 | 0.79 | 0.04 | 0.04 |
| 13 | mm | 26.20 | 0.00 | 0.15 | 0.79 | 0.04 | 0.04 |
| 14 | mm | 26.20 | 0.00 | 0.15 | 0.79 | 0.04 | 0.04 |
| 15 | mm | 26.20 | 0.00 | 0.15 | 0.79 | 0.04 | 0.04 |
| 16 | mm | 26.20 | 0.00 | 0.15 | 0.79 | 0.04 | 0.04 |
| 17 | mm | 26.20 | 0.00 | 0.15 | 0.79 | 0.04 | 0.04 |
| 18 | mm | 26.20 | 0.00 | 0.15 | 0.79 | 0.04 | 0.04 |
| 19 | mm | 26.20 | 0.02 | 0.66 | 0.46 | 0.08 | 0.27 |
| 20 | mm | 26.20 | 0.00 | 0.15 | 0.79 | 0.04 | 0.04 |
| 21 | mm | 26.20 | 0.00 | 0.15 | 0.79 | 0.04 | 0.04 |
| 22 | mm | 26.20 | 0.02 | 0.60 | 0.82 | 0.19 | 0.15 |
| 23 | mm | 26.20 | 0.01 | 0.36 | 0.57 | 0.08 | 0.11 |
| 24 | mm | 26.20 | 0.02 | 0.53 | 0.71 | 0.15 | 0.15 |
| 25 | mm | 26.20 | 0.01 | 0.69 | 0.31 | 0.04 | 0.31 |
| 26 | mm | 26.20 | 0.00 | 0.15 | 0.79 | 0.04 | 0.04 |

**Appendix Table 14** (Continued)

| # | Scale Units | Scale Factor | Area | Perimeter | Circularity | Height | Width |
|---|---|---|---|---|---|---|---|
| 27 | mm | 26.20 | 0.00 | 0.15 | 0.79 | 0.04 | 0.04 |
| 28 | mm | 26.20 | 0.00 | 0.15 | 0.79 | 0.04 | 0.04 |
| 29 | mm | 26.20 | 7.58 | 37.34 | 0.07 | 2.67 | 14.58 |
| 30 | mm | 26.20 | 0.03 | 0.79 | 0.64 | 0.19 | 0.27 |
| 31 | mm | 26.20 | 0.00 | 0.15 | 0.79 | 0.04 | 0.04 |
| 32 | mm | 26.20 | 15.04 | 87.21 | 0.02 | 3.05 | 32.18 |
| 33 | mm | 26.20 | 12.09 | 71.84 | 0.03 | 2.82 | 25.19 |
| 34 | mm | 26.20 | 0.00 | 0.15 | 0.79 | 0.04 | 0.04 |
| 35 | mm | 26.20 | 0.24 | 3.32 | 0.28 | 0.46 | 1.37 |
| 36 | mm | 26.20 | 0.02 | 0.61 | 0.60 | 0.19 | 0.19 |
| 37 | mm | 26.20 | 0.00 | 0.15 | 0.79 | 0.04 | 0.04 |
| 38 | mm | 26.20 | 0.01 | 0.35 | 0.76 | 0.11 | 0.08 |
| 39 | mm | 26.20 | 0.00 | 0.15 | 0.79 | 0.04 | 0.04 |
| 40 | mm | 26.20 | 0.00 | 0.15 | 0.79 | 0.04 | 0.04 |
| 41 | mm | 26.20 | 0.00 | 0.15 | 0.79 | 0.04 | 0.04 |
| 42 | mm | 26.20 | 0.00 | 0.15 | 0.79 | 0.04 | 0.04 |
| 43 | mm | 26.20 | 0.00 | 0.15 | 0.79 | 0.04 | 0.04 |
| 44 | mm | 26.20 | 0.00 | 0.15 | 0.79 | 0.04 | 0.04 |
| 45 | mm | 26.20 | 2.22 | 15.20 | 0.12 | 1.34 | 5.65 |
| 46 | mm | 26.20 | 0.00 | 0.15 | 0.79 | 0.04 | 0.04 |
| 47 | mm | 26.20 | 0.00 | 0.23 | 0.70 | 0.04 | 0.08 |
| 48 | mm | 26.20 | 0.00 | 0.15 | 0.79 | 0.04 | 0.04 |
| 49 | mm | 26.20 | 0.00 | 0.15 | 0.79 | 0.04 | 0.04 |
| 50 | mm | 26.20 | 0.00 | 0.23 | 0.70 | 0.04 | 0.08 |
| 51 | mm | 26.20 | 0.00 | 0.27 | 0.74 | 0.08 | 0.08 |
| 52 | mm | 26.20 | 0.01 | 0.46 | 0.62 | 0.11 | 0.15 |

**Appendix Table 14** (Continued)

| # | Scale Units | Scale Factor | Area | Perimeter | Circularity | Height | Width |
|---|---|---|---|---|---|---|---|
| 53 | mm | 26.20 | 0.00 | 0.23 | 0.70 | 0.04 | 0.08 |
| 54 | mm | 26.20 | 0.00 | 0.23 | 0.70 | 0.08 | 0.04 |
| 55 | mm | 26.20 | 0.00 | 0.15 | 0.79 | 0.04 | 0.04 |
| 56 | mm | 26.20 | 0.00 | 0.23 | 0.70 | 0.04 | 0.08 |
| 57 | mm | 26.20 | 0.00 | 0.15 | 0.79 | 0.04 | 0.04 |
| 58 | mm | 26.20 | 0.01 | 0.31 | 0.74 | 0.11 | 0.08 |
| 59 | mm | 26.20 | 0.02 | 0.75 | 0.42 | 0.11 | 0.31 |
| 60 | mm | 26.20 | 0.00 | 0.15 | 0.79 | 0.04 | 0.04 |
| 61 | mm | 26.20 | 0.00 | 0.23 | 0.70 | 0.08 | 0.04 |
| 62 | mm | 26.20 | 0.01 | 0.39 | 0.72 | 0.15 | 0.08 |
| 63 | mm | 26.20 | 0.00 | 0.23 | 0.70 | 0.04 | 0.08 |
| Total Area | | 112.41 | | | | | |

**Appendix Table 15** Crack area calculation for specimen M20PVA2

| # | Scale Units | Scale Factor | Area | Perimeter | Circularity | Height | Width |
|---|---|---|---|---|---|---|---|
| 1 | mm | 19.50 | 39.94 | 291.22 | 0.01 | 18.62 | 104.05 |
| 2 | mm | 19.50 | 9.40 | 52.63 | 0.04 | 3.33 | 19.33 |
| 3 | mm | 19.50 | 4.94 | 34.95 | 0.05 | 4.10 | 14.62 |
| 4 | mm | 19.50 | 0.00 | 0.21 | 0.79 | 0.05 | 0.05 |
| 5 | mm | 19.50 | 0.00 | 0.21 | 0.79 | 0.05 | 0.05 |
| 6 | mm | 19.50 | 0.00 | 0.21 | 0.79 | 0.05 | 0.05 |
| 7 | mm | 19.50 | 0.11 | 1.95 | 0.36 | 0.62 | 0.62 |
| 8 | mm | 19.50 | 0.00 | 0.21 | 0.79 | 0.05 | 0.05 |
| 9 | mm | 19.50 | 0.05 | 0.83 | 0.86 | 0.21 | 0.26 |
| 10 | mm | 19.50 | 0.04 | 1.05 | 0.48 | 0.15 | 0.41 |
| 11 | mm | 19.50 | 0.01 | 0.31 | 0.70 | 0.05 | 0.10 |
| 12 | mm | 19.50 | 0.08 | 1.82 | 0.30 | 0.31 | 0.77 |
| 13 | mm | 19.50 | 0.02 | 0.72 | 0.38 | 0.05 | 0.31 |
| 14 | mm | 19.50 | 0.14 | 2.73 | 0.23 | 0.26 | 1.23 |
| 15 | mm | 19.50 | 0.00 | 0.21 | 0.79 | 0.05 | 0.05 |
| 16 | mm | 19.50 | 0.01 | 0.31 | 0.70 | 0.05 | 0.10 |
| 17 | mm | 19.50 | 0.77 | 7.92 | 0.15 | 1.23 | 3.13 |
| 18 | mm | 19.50 | 2.45 | 15.98 | 0.12 | 2.05 | 6.41 |
| 19 | mm | 19.50 | 0.17 | 2.04 | 0.51 | 0.36 | 0.82 |
| 20 | mm | 19.50 | 0.00 | 0.21 | 0.79 | 0.05 | 0.05 |
| 21 | mm | 19.50 | 0.00 | 0.21 | 0.79 | 0.05 | 0.05 |
| 22 | mm | 19.50 | 1.70 | 14.93 | 0.10 | 1.33 | 6.31 |
| 23 | mm | 19.50 | 0.01 | 0.41 | 0.79 | 0.10 | 0.10 |
| 24 | mm | 19.50 | 0.01 | 0.31 | 0.70 | 0.05 | 0.10 |
| 25 | mm | 19.50 | 1.09 | 5.28 | 0.49 | 1.79 | 1.18 |
| 26 | mm | 19.50 | 0.44 | 7.24 | 0.11 | 0.62 | 3.18 |

**Appendix Table 15** (Continued)

| # | Scale Units | Scale Factor | Area | Perimeter | Circularity | Height | Width |
|---|---|---|---|---|---|---|---|
| 27 | mm | 19.50 | 0.07 | 1.53 | 0.37 | 0.15 | 0.67 |
| 28 | mm | 19.50 | 0.00 | 0.21 | 0.79 | 0.05 | 0.05 |
| 29 | mm | 19.50 | 0.04 | 1.02 | 0.47 | 0.15 | 0.41 |
| 30 | mm | 19.50 | 0.01 | 0.31 | 0.70 | 0.05 | 0.10 |
| 31 | mm | 19.50 | 0.45 | 5.00 | 0.23 | 0.51 | 2.15 |
| 32 | mm | 19.50 | 0.01 | 0.42 | 0.74 | 0.10 | 0.15 |
| 33 | mm | 19.50 | 0.01 | 0.48 | 0.57 | 0.15 | 0.10 |
| 34 | mm | 19.50 | 6.14 | 30.84 | 0.08 | 2.77 | 13.13 |
| 35 | mm | 19.50 | 0.01 | 0.31 | 0.70 | 0.10 | 0.05 |
| 36 | mm | 19.50 | 0.00 | 0.21 | 0.79 | 0.05 | 0.05 |
| 37 | mm | 19.50 | 1.14 | 8.57 | 0.20 | 1.54 | 3.23 |
| 38 | mm | 19.50 | 0.01 | 0.48 | 0.57 | 0.15 | 0.10 |
| 39 | mm | 19.50 | 2.18 | 19.48 | 0.07 | 2.46 | 7.44 |
| 40 | mm | 19.50 | 0.01 | 0.31 | 0.70 | 0.05 | 0.10 |
| 41 | mm | 19.50 | 0.01 | 0.51 | 0.50 | 0.05 | 0.21 |
| 42 | mm | 19.50 | 0.01 | 0.62 | 0.44 | 0.05 | 0.26 |
| 43 | mm | 19.50 | 0.00 | 0.21 | 0.79 | 0.05 | 0.05 |
| 44 | mm | 19.50 | 0.00 | 0.21 | 0.79 | 0.05 | 0.05 |
| 45 | mm | 19.50 | 1.54 | 9.80 | 0.20 | 1.38 | 3.85 |
| 46 | mm | 19.50 | 0.01 | 0.41 | 0.59 | 0.15 | 0.05 |
| 47 | mm | 19.50 | 0.05 | 0.95 | 0.66 | 0.15 | 0.36 |
| 48 | mm | 19.50 | 0.03 | 0.63 | 0.84 | 0.15 | 0.21 |
| 49 | mm | 19.50 | 0.11 | 2.08 | 0.33 | 0.46 | 0.82 |
| 50 | mm | 19.50 | 0.00 | 0.21 | 0.79 | 0.05 | 0.05 |
| 51 | mm | 19.50 | 0.00 | 0.21 | 0.79 | 0.05 | 0.05 |
| 52 | mm | 19.50 | 0.18 | 2.35 | 0.41 | 0.46 | 0.87 |

**Appendix Table 15** (Continued)

| # | Scale Units | Scale Factor | Area | Perimeter | Circularity | Height | Width |
|---|---|---|---|---|---|---|---|
| 53 | mm | 19.50 | 0.01 | 0.54 | 0.57 | 0.21 | 0.10 |
| 54 | mm | 19.50 | 0.00 | 0.21 | 0.79 | 0.05 | 0.05 |
| 55 | mm | 19.50 | 0.01 | 0.31 | 0.70 | 0.10 | 0.05 |
| 56 | mm | 19.50 | 0.00 | 0.21 | 0.79 | 0.05 | 0.05 |
| 57 | mm | 19.50 | 0.01 | 0.31 | 0.70 | 0.05 | 0.10 |
| 58 | mm | 19.50 | 0.02 | 0.71 | 0.52 | 0.21 | 0.26 |
| 59 | mm | 19.50 | 0.01 | 0.37 | 0.74 | 0.10 | 0.10 |
| 60 | mm | 19.50 | 0.00 | 0.21 | 0.79 | 0.05 | 0.05 |
| 61 | mm | 19.50 | 0.00 | 0.21 | 0.79 | 0.05 | 0.05 |
| 62 | mm | 19.50 | 0.00 | 0.21 | 0.79 | 0.05 | 0.05 |
| 63 | mm | 19.50 | 0.01 | 0.31 | 0.70 | 0.05 | 0.10 |
| 64 | mm | 19.50 | 0.01 | 0.31 | 0.70 | 0.05 | 0.10 |
| 65 | mm | 19.50 | 0.00 | 0.21 | 0.79 | 0.05 | 0.05 |
| 66 | mm | 19.50 | 0.01 | 0.31 | 0.70 | 0.05 | 0.10 |
| 67 | mm | 19.50 | 0.00 | 0.21 | 0.79 | 0.05 | 0.05 |
| 68 | mm | 19.50 | 0.00 | 0.21 | 0.79 | 0.05 | 0.05 |
| 69 | mm | 19.50 | 0.00 | 0.21 | 0.79 | 0.05 | 0.05 |
| 70 | mm | 19.50 | 0.00 | 0.21 | 0.79 | 0.05 | 0.05 |
| 71 | mm | 19.50 | 3.44 | 18.30 | 0.13 | 1.69 | 7.69 |
| 72 | mm | 19.50 | 0.07 | 1.19 | 0.61 | 0.21 | 0.41 |
| 73 | mm | 19.50 | 0.01 | 0.31 | 0.70 | 0.10 | 0.05 |
| 74 | mm | 19.50 | 0.01 | 0.31 | 0.70 | 0.05 | 0.10 |
| 75 | mm | 19.50 | 0.03 | 0.95 | 0.44 | 0.10 | 0.41 |
| 76 | mm | 19.50 | 0.00 | 0.21 | 0.79 | 0.05 | 0.05 |
| 77 | mm | 19.50 | 0.06 | 1.21 | 0.54 | 0.41 | 0.26 |
| 78 | mm | 19.50 | 0.00 | 0.21 | 0.79 | 0.05 | 0.05 |

**Appendix Table 15** (Continued)

| # | Scale Units | Scale Factor | Area | Perimeter | Circularity | Height | Width |
|---|---|---|---|---|---|---|---|
| 79 | mm | 19.50 | 0.00 | 0.21 | 0.79 | 0.05 | 0.05 |
| 80 | mm | 19.50 | 2.72 | 21.01 | 0.08 | 1.74 | 8.72 |
| 81 | mm | 19.50 | 0.00 | 0.21 | 0.79 | 0.05 | 0.05 |
| 82 | mm | 19.50 | 0.01 | 0.31 | 0.70 | 0.05 | 0.10 |
| 83 | mm | 19.50 | 0.01 | 0.31 | 0.70 | 0.05 | 0.10 |
| 84 | mm | 19.50 | 0.01 | 0.31 | 0.70 | 0.05 | 0.10 |
| 85 | mm | 19.50 | 0.00 | 0.21 | 0.79 | 0.05 | 0.05 |
| 86 | mm | 19.50 | 0.01 | 0.41 | 0.79 | 0.10 | 0.10 |
| 87 | mm | 19.50 | 0.00 | 0.21 | 0.79 | 0.05 | 0.05 |
| Total Area | | 79.87 | | | | | |

**Appendix Table 16** Crack area calculation for specimen M20PVA3

| # | Scale Units | Scale Factor | Area | Perimeter | Circularity | Height | Width |
|---|---|---|---|---|---|---|---|
| 1 | mm | 17.40 | 34.57 | 266.82 | 0.01 | 17.47 | 101.90 |
| 2 | mm | 17.40 | 0.23 | 2.98 | 0.32 | 0.40 | 1.26 |
| 3 | mm | 17.40 | 0.00 | 0.23 | 0.79 | 0.06 | 0.06 |
| 4 | mm | 17.40 | 0.25 | 2.98 | 0.36 | 0.34 | 1.26 |
| 5 | mm | 17.40 | 0.01 | 0.34 | 0.70 | 0.11 | 0.06 |
| 6 | mm | 17.40 | 0.00 | 0.23 | 0.79 | 0.06 | 0.06 |
| 7 | mm | 17.40 | 0.04 | 0.84 | 0.71 | 0.29 | 0.17 |
| 8 | mm | 17.40 | 0.28 | 3.87 | 0.24 | 0.57 | 1.61 |
| 9 | mm | 17.40 | 0.07 | 1.07 | 0.77 | 0.23 | 0.34 |
| 10 | mm | 17.40 | 0.00 | 0.23 | 0.79 | 0.06 | 0.06 |
| 11 | mm | 17.40 | 0.03 | 0.75 | 0.66 | 0.17 | 0.29 |
| 12 | mm | 17.40 | 0.36 | 4.38 | 0.24 | 0.80 | 1.67 |
| 13 | mm | 17.40 | 0.20 | 2.94 | 0.29 | 0.34 | 1.26 |
| 14 | mm | 17.40 | 0.51 | 6.19 | 0.17 | 0.98 | 2.36 |
| 15 | mm | 17.40 | 0.01 | 0.34 | 0.70 | 0.11 | 0.06 |
| 16 | mm | 17.40 | 0.27 | 3.20 | 0.33 | 0.86 | 0.98 |
| 17 | mm | 17.40 | 0.00 | 0.23 | 0.79 | 0.06 | 0.06 |
| 18 | mm | 17.40 | 0.40 | 4.58 | 0.24 | 0.63 | 1.61 |
| 19 | mm | 17.40 | 0.02 | 0.52 | 0.76 | 0.11 | 0.17 |
| 20 | mm | 17.40 | 0.01 | 0.57 | 0.50 | 0.06 | 0.23 |
| 21 | mm | 17.40 | 0.06 | 1.19 | 0.52 | 0.17 | 0.40 |
| 22 | mm | 17.40 | 0.19 | 2.70 | 0.33 | 0.34 | 1.09 |
| 23 | mm | 17.40 | 0.06 | 1.57 | 0.29 | 0.11 | 0.69 |
| 24 | mm | 17.40 | 0.00 | 0.23 | 0.79 | 0.06 | 0.06 |
| 25 | mm | 17.40 | 0.01 | 0.34 | 0.70 | 0.06 | 0.11 |
| 26 | mm | 17.40 | 0.00 | 0.23 | 0.79 | 0.06 | 0.06 |

**Appendix Table 16** (Continued)

| # | Scale Units | Scale Factor | Area | Perimeter | Circularity | Height | Width |
|---|---|---|---|---|---|---|---|
| 27 | mm | 17.40 | 0.00 | 0.23 | 0.79 | 0.06 | 0.06 |
| 28 | mm | 17.40 | 0.12 | 2.46 | 0.25 | 0.29 | 0.98 |
| 29 | mm | 17.40 | 0.05 | 1.28 | 0.36 | 0.17 | 0.52 |
| 30 | mm | 17.40 | 0.01 | 0.41 | 0.74 | 0.11 | 0.11 |
| 31 | mm | 17.40 | 0.03 | 0.98 | 0.43 | 0.17 | 0.40 |
| 32 | mm | 17.40 | 0.00 | 0.23 | 0.79 | 0.06 | 0.06 |
| 33 | mm | 17.40 | 0.05 | 1.01 | 0.64 | 0.17 | 0.40 |
| 34 | mm | 17.40 | 0.23 | 3.60 | 0.22 | 0.34 | 1.49 |
| 35 | mm | 17.40 | 0.01 | 0.41 | 0.74 | 0.11 | 0.11 |
| 36 | mm | 17.40 | 0.00 | 0.23 | 0.79 | 0.06 | 0.06 |
| 37 | mm | 17.40 | 0.00 | 0.23 | 0.79 | 0.06 | 0.06 |
| 38 | mm | 17.40 | 0.01 | 0.57 | 0.50 | 0.06 | 0.23 |
| 39 | mm | 17.40 | 0.43 | 4.71 | 0.24 | 0.57 | 1.90 |
| 40 | mm | 17.40 | 6.30 | 39.84 | 0.05 | 2.30 | 15.98 |
| 41 | mm | 17.40 | 0.63 | 4.78 | 0.35 | 0.63 | 2.01 |
| 42 | mm | 17.40 | 0.58 | 5.42 | 0.25 | 0.57 | 2.18 |
| 43 | mm | 17.40 | 0.83 | 7.83 | 0.17 | 1.78 | 2.82 |
| 44 | mm | 17.40 | 0.00 | 0.23 | 0.79 | 0.06 | 0.06 |
| 45 | mm | 17.40 | 0.03 | 0.80 | 0.58 | 0.23 | 0.23 |
| 46 | mm | 17.40 | 0.47 | 3.64 | 0.45 | 0.52 | 1.32 |
| 47 | mm | 17.40 | 11.04 | 61.56 | 0.04 | 4.14 | 22.99 |
| 48 | mm | 17.40 | 0.03 | 0.95 | 0.46 | 0.11 | 0.40 |
| 49 | mm | 17.40 | 0.41 | 4.78 | 0.23 | 0.57 | 2.01 |
| 50 | mm | 17.40 | 1.20 | 8.42 | 0.21 | 1.26 | 3.22 |
| 51 | mm | 17.40 | 0.86 | 8.74 | 0.14 | 0.57 | 3.79 |
| 52 | mm | 17.40 | 2.53 | 14.58 | 0.15 | 1.32 | 5.40 |

**Appendix Table 16** (Continued)

| # | Scale Units | Scale Factor | Area | Perimeter | Circularity | Height | Width |
|---|---|---|---|---|---|---|---|
| 53 | mm | 17.40 | 0.00 | 0.23 | 0.79 | 0.06 | 0.06 |
| 54 | mm | 17.40 | 0.00 | 0.23 | 0.79 | 0.06 | 0.06 |
| 55 | mm | 17.40 | 0.00 | 0.23 | 0.79 | 0.06 | 0.06 |
| 56 | mm | 17.40 | 0.86 | 7.16 | 0.21 | 0.69 | 3.05 |
| 57 | mm | 17.40 | 1.76 | 11.27 | 0.17 | 0.98 | 4.48 |
| 58 | mm | 17.40 | 0.01 | 0.34 | 0.70 | 0.11 | 0.06 |
| 59 | mm | 17.40 | 2.61 | 17.12 | 0.11 | 2.41 | 6.49 |
| 60 | mm | 17.40 | 0.00 | 0.23 | 0.79 | 0.06 | 0.06 |
| 61 | mm | 17.40 | 0.09 | 1.59 | 0.45 | 0.46 | 0.46 |
| 62 | mm | 17.40 | 0.09 | 1.42 | 0.53 | 0.34 | 0.52 |
| 63 | mm | 17.40 | 0.00 | 0.23 | 0.79 | 0.06 | 0.06 |
| 64 | mm | 17.40 | 0.14 | 2.16 | 0.37 | 0.29 | 0.92 |
| 65 | mm | 17.40 | 0.00 | 0.23 | 0.79 | 0.06 | 0.06 |
| 66 | mm | 17.40 | 0.02 | 0.72 | 0.56 | 0.11 | 0.29 |
| 67 | mm | 17.40 | 0.01 | 0.46 | 0.59 | 0.06 | 0.17 |
| 68 | mm | 17.40 | 0.00 | 0.23 | 0.79 | 0.06 | 0.06 |
| 69 | mm | 17.40 | 0.01 | 0.41 | 0.74 | 0.11 | 0.11 |
| 70 | mm | 17.40 | 0.05 | 1.06 | 0.59 | 0.23 | 0.40 |
| 71 | mm | 17.40 | 0.00 | 0.23 | 0.79 | 0.06 | 0.06 |
| 72 | mm | 17.40 | 0.01 | 0.57 | 0.50 | 0.06 | 0.23 |
| Total Area | | | 69.14 | | | | |

**Appendix Table 17** Crack area calculation for specimen M20SF1

| # | Scale Units | Scale Factor | Area | Perimeter | Circularity | Height | Width |
|---|---|---|---|---|---|---|---|
| 1 | mm | 24.90 | 78.97 | 311.61 | 0.01 | 9.04 | 104.70 |
| 2 | mm | 24.90 | 0.00 | 0.16 | 0.79 | 0.04 | 0.04 |
| 3 | mm | 24.90 | 2.38 | 17.04 | 0.10 | 2.33 | 4.54 |
| 4 | mm | 24.90 | 0.46 | 4.21 | 0.32 | 0.80 | 1.65 |
| 5 | mm | 24.90 | 0.01 | 0.33 | 0.74 | 0.08 | 0.12 |
| 6 | mm | 24.90 | 0.00 | 0.16 | 0.79 | 0.04 | 0.04 |
| 7 | mm | 24.90 | 0.00 | 0.16 | 0.79 | 0.04 | 0.04 |
| 8 | mm | 24.90 | 0.00 | 0.16 | 0.79 | 0.04 | 0.04 |
| 9 | mm | 24.90 | 0.01 | 0.33 | 0.74 | 0.12 | 0.08 |
| 10 | mm | 24.90 | 0.00 | 0.24 | 0.70 | 0.04 | 0.08 |
| 11 | mm | 24.90 | 0.00 | 0.16 | 0.79 | 0.04 | 0.04 |
| 12 | mm | 24.90 | 0.55 | 5.16 | 0.26 | 0.64 | 2.13 |
| 13 | mm | 24.90 | 0.00 | 0.16 | 0.79 | 0.04 | 0.04 |
| 14 | mm | 24.90 | 0.10 | 1.86 | 0.35 | 0.20 | 0.76 |
| 15 | mm | 24.90 | 2.18 | 12.64 | 0.17 | 1.12 | 4.90 |
| 16 | mm | 24.90 | 0.00 | 0.16 | 0.79 | 0.04 | 0.04 |
| 17 | mm | 24.90 | 0.00 | 0.16 | 0.79 | 0.04 | 0.04 |
| 18 | mm | 24.90 | 0.00 | 0.16 | 0.79 | 0.04 | 0.04 |
| 19 | mm | 24.90 | 0.01 | 0.44 | 0.62 | 0.16 | 0.12 |
| 20 | mm | 24.90 | 0.00 | 0.16 | 0.79 | 0.04 | 0.04 |
| 21 | mm | 24.90 | 8.46 | 27.54 | 0.14 | 2.33 | 11.24 |
| 22 | mm | 24.90 | 0.01 | 0.52 | 0.53 | 0.12 | 0.16 |
| 23 | mm | 24.90 | 31.55 | 94.01 | 0.04 | 5.98 | 36.51 |
| 24 | mm | 24.90 | 1.59 | 7.40 | 0.37 | 1.16 | 2.77 |
| 25 | mm | 24.90 | 0.00 | 0.24 | 0.70 | 0.04 | 0.08 |
| 26 | mm | 24.90 | 0.01 | 0.32 | 0.79 | 0.08 | 0.08 |

**Appendix Table 17** (Continued)

| # | Scale Units | Scale Factor | Area | Perimeter | Circularity | Height | Width |
|---|---|---|---|---|---|---|---|
| 27 | mm | 24.90 | 8.06 | 27.06 | 0.14 | 2.05 | 10.44 |
| 28 | mm | 24.90 | 0.02 | 0.62 | 0.59 | 0.16 | 0.20 |
| 29 | mm | 24.90 | 0.00 | 0.16 | 0.79 | 0.04 | 0.04 |
| 30 | mm | 24.90 | 1.24 | 10.78 | 0.13 | 2.69 | 3.57 |
| 31 | mm | 24.90 | 0.00 | 0.16 | 0.79 | 0.04 | 0.04 |
| 32 | mm | 24.90 | 0.00 | 0.24 | 0.70 | 0.04 | 0.08 |
| 33 | mm | 24.90 | 0.00 | 0.16 | 0.79 | 0.04 | 0.04 |
| 34 | mm | 24.90 | 0.00 | 0.24 | 0.70 | 0.04 | 0.08 |
| 35 | mm | 24.90 | 0.00 | 0.16 | 0.79 | 0.04 | 0.04 |
| 36 | mm | 24.90 | 0.01 | 0.40 | 0.50 | 0.04 | 0.16 |
| 37 | mm | 24.90 | 15.92 | 61.21 | 0.05 | 3.65 | 22.13 |
| 38 | mm | 24.90 | 0.00 | 0.16 | 0.79 | 0.04 | 0.04 |
| 39 | mm | 24.90 | 0.03 | 0.79 | 0.52 | 0.28 | 0.16 |
| 40 | mm | 24.90 | 0.00 | 0.32 | 0.59 | 0.12 | 0.04 |
| 41 | mm | 24.90 | 0.00 | 0.24 | 0.70 | 0.08 | 0.04 |
| 42 | mm | 24.90 | 0.00 | 0.16 | 0.79 | 0.04 | 0.04 |
| 43 | mm | 24.90 | 0.00 | 0.32 | 0.59 | 0.04 | 0.12 |
| 44 | mm | 24.90 | 0.00 | 0.24 | 0.70 | 0.04 | 0.08 |
| 45 | mm | 24.90 | 1.89 | 11.67 | 0.17 | 0.92 | 4.74 |
| 46 | mm | 24.90 | 4.26 | 17.51 | 0.17 | 2.25 | 6.47 |
| 47 | mm | 24.90 | 0.00 | 0.24 | 0.70 | 0.08 | 0.04 |
| 48 | mm | 24.90 | 0.02 | 0.53 | 0.80 | 0.16 | 0.12 |
| 49 | mm | 24.90 | 0.02 | 0.63 | 0.51 | 0.16 | 0.20 |
| 50 | mm | 24.90 | 0.00 | 0.24 | 0.70 | 0.04 | 0.08 |
| 51 | mm | 24.90 | 0.00 | 0.24 | 0.70 | 0.04 | 0.08 |
| 52 | mm | 24.90 | 0.00 | 0.16 | 0.79 | 0.04 | 0.04 |

**Appendix Table 17** (Continued)

| # | Scale Units | Scale Factor | Area | Perimeter | Circularity | Height | Width |
|---|---|---|---|---|---|---|---|
| 53 | mm | 24.90 | 0.11 | 2.07 | 0.32 | 0.36 | 0.76 |
| 54 | mm | 24.90 | 0.03 | 1.02 | 0.33 | 0.12 | 0.44 |
| Total Area | | | 157.94 | | | | |

**Appendix Table 18** Crack area calculation for specimen M20SF2

| # | Scale Units | Scale Factor | Area | Perimeter | Circularity | Height | Width |
|---|---|---|---|---|---|---|---|
| 1 | mm | 23.20 | 74.63 | 195.04 | 0.02 | 64.96 | 13.79 |
| 2 | mm | 23.20 | 49.03 | 113.44 | 0.05 | 40.22 | 4.40 |
| 3 | mm | 23.20 | 11.60 | 32.88 | 0.13 | 11.51 | 3.45 |
| 4 | mm | 23.20 | 9.61 | 22.57 | 0.24 | 8.15 | 4.27 |
| 5 | mm | 23.20 | 3.51 | 12.88 | 0.27 | 3.92 | 2.76 |
| 6 | mm | 23.20 | 0.70 | 8.93 | 0.11 | 3.79 | 0.99 |
| 7 | mm | 23.20 | 0.15 | 3.05 | 0.20 | 1.25 | 0.30 |
| 8 | mm | 23.20 | 0.01 | 0.34 | 0.59 | 0.13 | 0.04 |
| 9 | mm | 23.20 | 0.00 | 0.26 | 0.70 | 0.09 | 0.04 |
| 10 | mm | 23.20 | 0.00 | 0.17 | 0.79 | 0.04 | 0.04 |
| 11 | mm | 23.20 | 0.00 | 0.17 | 0.79 | 0.04 | 0.04 |
| 12 | mm | 23.20 | 0.00 | 0.17 | 0.79 | 0.04 | 0.04 |
| 13 | mm | 23.20 | 0.00 | 0.17 | 0.79 | 0.04 | 0.04 |
| 14 | mm | 23.20 | 48.84 | 151.76 | 0.03 | 102.33 | 16.34 |
| 15 | mm | 23.20 | 19.55 | 52.91 | 0.09 | 19.14 | 4.18 |
| 16 | mm | 23.20 | 16.60 | 44.33 | 0.11 | 14.44 | 3.49 |
| 17 | mm | 23.20 | 12.20 | 41.69 | 0.09 | 14.66 | 4.83 |
| 18 | mm | 23.20 | 0.16 | 3.15 | 0.21 | 1.42 | 0.13 |
| 19 | mm | 23.20 | 0.13 | 2.80 | 0.21 | 1.25 | 0.22 |
| 20 | mm | 23.20 | 0.11 | 1.72 | 0.45 | 0.60 | 0.30 |
| 21 | mm | 23.20 | 0.02 | 0.66 | 0.59 | 0.22 | 0.17 |
| 22 | mm | 23.20 | 0.01 | 0.54 | 0.56 | 0.22 | 0.09 |
| 23 | mm | 23.20 | 0.01 | 0.55 | 0.53 | 0.13 | 0.17 |
| 24 | mm | 23.20 | 0.01 | 0.34 | 0.59 | 0.13 | 0.04 |
| 25 | mm | 23.20 | 0.01 | 0.31 | 0.74 | 0.09 | 0.09 |
| 26 | mm | 23.20 | 0.00 | 0.26 | 0.70 | 0.09 | 0.04 |

**Appendix Table 18** (Continued)

| # | Scale Units | Scale Factor | Area | Perimeter | Circularity | Height | Width |
|---|---|---|---|---|---|---|---|
| 27 | mm | 23.20 | 0.00 | 0.26 | 0.70 | 0.09 | 0.04 |
| 28 | mm | 23.20 | 0.00 | 0.17 | 0.79 | 0.04 | 0.04 |
| 29 | mm | 23.20 | 0.00 | 0.17 | 0.79 | 0.04 | 0.04 |
| 30 | mm | 23.20 | 0.00 | 0.17 | 0.79 | 0.04 | 0.04 |
| 31 | mm | 23.20 | 0.00 | 0.17 | 0.79 | 0.04 | 0.04 |
| 32 | mm | 23.20 | 0.00 | 0.17 | 0.79 | 0.04 | 0.04 |
| 33 | mm | 23.20 | 0.00 | 0.17 | 0.79 | 0.04 | 0.04 |
| 34 | mm | 23.20 | 0.00 | 0.17 | 0.79 | 0.04 | 0.04 |
| 35 | mm | 23.20 | 0.00 | 0.17 | 0.79 | 0.04 | 0.04 |
| 36 | mm | 23.20 | 0.00 | 0.17 | 0.79 | 0.04 | 0.04 |
| 37 | mm | 23.20 | 0.00 | 0.17 | 0.79 | 0.04 | 0.04 |
| 38 | mm | 23.20 | 0.00 | 0.17 | 0.79 | 0.04 | 0.04 |
| 39 | mm | 23.20 | 0.00 | 0.17 | 0.79 | 0.04 | 0.04 |
| 40 | mm | 23.20 | 0.00 | 0.17 | 0.79 | 0.04 | 0.04 |
| Total Area | | | 123.66 | | | | |

**Appendix Table 19** Crack area calculation for specimen M20SF3

| # | Scale Units | Scale Factor | Area | Perimeter | Circularity | Height | Width |
|---|---|---|---|---|---|---|---|
| 1 | mm | 22.80 | 63.44 | 295.81 | 0.01 | 10.09 | 104.78 |
| 2 | mm | 22.80 | 2.09 | 11.70 | 0.19 | 1.45 | 4.30 |
| 3 | mm | 22.80 | 33.30 | 111.72 | 0.03 | 6.97 | 41.58 |
| 4 | mm | 22.80 | 0.00 | 0.18 | 0.79 | 0.04 | 0.04 |
| 5 | mm | 22.80 | 0.02 | 0.55 | 0.72 | 0.13 | 0.18 |
| 6 | mm | 22.80 | 0.03 | 1.25 | 0.28 | 0.35 | 0.35 |
| 7 | mm | 22.80 | 1.30 | 9.60 | 0.18 | 2.41 | 3.29 |
| 8 | mm | 22.80 | 0.01 | 0.61 | 0.38 | 0.04 | 0.26 |
| 9 | mm | 22.80 | 0.01 | 0.65 | 0.40 | 0.09 | 0.26 |
| 10 | mm | 22.80 | 0.79 | 9.77 | 0.10 | 1.05 | 4.21 |
| 11 | mm | 22.80 | 4.41 | 24.94 | 0.09 | 2.28 | 9.47 |
| 12 | mm | 22.80 | 0.01 | 0.31 | 0.74 | 0.09 | 0.09 |
| 13 | mm | 22.80 | 0.00 | 0.18 | 0.79 | 0.04 | 0.04 |
| 14 | mm | 22.80 | 0.08 | 1.54 | 0.45 | 0.18 | 0.66 |
| 15 | mm | 22.80 | 0.01 | 0.31 | 0.74 | 0.09 | 0.09 |
| 16 | mm | 22.80 | 0.00 | 0.18 | 0.79 | 0.04 | 0.04 |
| 17 | mm | 22.80 | 0.00 | 0.26 | 0.70 | 0.04 | 0.09 |
| 18 | mm | 22.80 | 1.24 | 8.25 | 0.23 | 1.58 | 3.03 |
| 19 | mm | 22.80 | 0.00 | 0.18 | 0.79 | 0.04 | 0.04 |
| 20 | mm | 22.80 | 0.00 | 0.26 | 0.70 | 0.09 | 0.04 |
| 21 | mm | 22.80 | 0.00 | 0.18 | 0.79 | 0.04 | 0.04 |
| 22 | mm | 22.80 | 0.06 | 1.31 | 0.44 | 0.39 | 0.44 |
| 23 | mm | 22.80 | 4.99 | 22.95 | 0.12 | 2.28 | 9.17 |
| 24 | mm | 22.80 | 0.00 | 0.18 | 0.79 | 0.04 | 0.04 |
| 25 | mm | 22.80 | 0.00 | 0.18 | 0.79 | 0.04 | 0.04 |
| 26 | mm | 22.80 | 0.00 | 0.26 | 0.70 | 0.04 | 0.09 |

**Appendix Table 19** (Continued)

| # | Scale Units | Scale Factor | Area | Perimeter | Circularity | Height | Width |
|---|---|---|---|---|---|---|---|
| 27 | mm | 22.80 | 12.88 | 68.02 | 0.03 | 4.08 | 27.59 |
| 28 | mm | 22.80 | 0.58 | 7.28 | 0.14 | 0.83 | 3.03 |
| 29 | mm | 22.80 | 0.83 | 6.28 | 0.27 | 0.53 | 2.63 |
| 30 | mm | 22.80 | 0.00 | 0.18 | 0.79 | 0.04 | 0.04 |
| 31 | mm | 22.80 | 0.00 | 0.26 | 0.70 | 0.09 | 0.04 |
| 32 | mm | 22.80 | 0.76 | 6.31 | 0.24 | 0.96 | 1.97 |
| 33 | mm | 22.80 | 12.88 | 68.02 | 0.03 | 4.08 | 27.59 |
| Total Area | | | 126.88 | | | | |

**Appendix Table 20** Crack area calculation for specimen M30.

| # | Scale Units | Scale Factor | Area | Perimeter | Circularity | Height | Width |
|---|---|---|---|---|---|---|---|
| 1 | mm | 19.17 | 100.06 | 321.51 | 0.01 | 15.49 | 100.50 |
| 2 | mm | 19.17 | 0.01 | 0.31 | 0.70 | 0.05 | 0.10 |
| 3 | mm | 19.17 | 1.17 | 6.39 | 0.36 | 2.19 | 1.56 |
| 4 | mm | 19.17 | 0.01 | 0.31 | 0.70 | 0.10 | 0.05 |
| 5 | mm | 19.17 | 16.97 | 46.99 | 0.10 | 7.25 | 16.32 |
| 6 | mm | 19.17 | 0.05 | 1.23 | 0.43 | 0.47 | 0.26 |
| 7 | mm | 19.17 | 0.00 | 0.21 | 0.79 | 0.05 | 0.05 |
| 8 | mm | 19.17 | 0.01 | 0.31 | 0.70 | 0.05 | 0.10 |
| 9 | mm | 19.17 | 0.73 | 8.94 | 0.12 | 1.88 | 2.45 |
| 10 | mm | 19.17 | 0.01 | 0.31 | 0.70 | 0.05 | 0.10 |
| 11 | mm | 19.17 | 0.01 | 0.31 | 0.70 | 0.05 | 0.10 |
| 12 | mm | 19.17 | 0.00 | 0.21 | 0.79 | 0.05 | 0.05 |
| 13 | mm | 19.17 | 0.01 | 0.31 | 0.70 | 0.10 | 0.05 |
| 14 | mm | 19.17 | 0.01 | 0.31 | 0.70 | 0.10 | 0.05 |
| 15 | mm | 19.17 | 7.01 | 32.54 | 0.08 | 3.91 | 11.84 |
| 16 | mm | 19.17 | 0.00 | 0.21 | 0.79 | 0.05 | 0.05 |
| 17 | mm | 19.17 | 0.00 | 0.21 | 0.79 | 0.05 | 0.05 |
| 18 | mm | 19.17 | 0.12 | 1.63 | 0.58 | 0.47 | 0.47 |
| 19 | mm | 19.17 | 16.62 | 61.20 | 0.06 | 6.05 | 19.87 |
| 20 | mm | 19.17 | 0.01 | 0.49 | 0.57 | 0.10 | 0.16 |
| 21 | mm | 19.17 | 0.00 | 0.21 | 0.79 | 0.05 | 0.05 |
| 22 | mm | 19.17 | 0.00 | 0.21 | 0.79 | 0.05 | 0.05 |
| 23 | mm | 19.17 | 0.00 | 0.21 | 0.79 | 0.05 | 0.05 |
| 24 | mm | 19.17 | 0.01 | 0.52 | 0.50 | 0.05 | 0.21 |
| 25 | mm | 19.17 | 0.00 | 0.21 | 0.79 | 0.05 | 0.05 |
| 26 | mm | 19.17 | 8.04 | 29.48 | 0.12 | 4.33 | 9.44 |

**Appendix Table 20** (Continued)

| # | Scale Units | Scale Factor | Area | Perimeter | Circularity | Height | Width |
|---|---|---|---|---|---|---|---|
| 27 | mm | 19.17 | 0.02 | 0.83 | 0.44 | 0.16 | 0.31 |
| 28 | mm | 19.17 | 0.01 | 0.31 | 0.70 | 0.05 | 0.10 |
| 29 | mm | 19.17 | 0.00 | 0.21 | 0.79 | 0.05 | 0.05 |
| 30 | mm | 19.17 | 48.94 | 118.75 | 0.04 | 4.90 | 44.91 |
| 31 | mm | 19.17 | 0.00 | 0.21 | 0.79 | 0.05 | 0.05 |
| 32 | mm | 19.17 | 0.00 | 0.21 | 0.79 | 0.05 | 0.05 |
| 33 | mm | 19.17 | 0.00 | 0.21 | 0.79 | 0.05 | 0.05 |
| 34 | mm | 19.17 | 0.07 | 1.68 | 0.29 | 0.16 | 0.73 |
| 35 | mm | 19.17 | 0.00 | 0.21 | 0.79 | 0.05 | 0.05 |
| 36 | mm | 19.17 | 0.03 | 0.98 | 0.39 | 0.42 | 0.10 |
| 37 | mm | 19.17 | 0.02 | 0.80 | 0.42 | 0.31 | 0.10 |
| 38 | mm | 19.17 | 0.00 | 0.21 | 0.79 | 0.05 | 0.05 |
| 39 | mm | 19.17 | 0.00 | 0.21 | 0.79 | 0.05 | 0.05 |
| 40 | mm | 19.17 | 0.02 | 0.85 | 0.43 | 0.21 | 0.26 |
| 41 | mm | 19.17 | 0.01 | 0.63 | 0.44 | 0.26 | 0.05 |
| 42 | mm | 19.17 | 0.11 | 1.94 | 0.35 | 0.57 | 0.57 |
| Total Area | | | 200.12 | | | | |

**Appendix Table 21** Crack area calculation for specimen M30PVA1.

| # | Scale Units | Scale Factor | Area | Perimeter | Circularity | Height | Width |
|---|---|---|---|---|---|---|---|
| 1 | mm | 16.06 | 36.19 | 300.26 | 0.01 | 100.42 | 10.09 |
| 2 | mm | 16.06 | 2.76 | 12.22 | 0.23 | 4.17 | 2.12 |
| 3 | mm | 16.06 | 0.00 | 0.25 | 0.79 | 0.06 | 0.06 |
| 4 | mm | 16.06 | 0.01 | 0.50 | 0.59 | 0.06 | 0.19 |
| 5 | mm | 16.06 | 0.88 | 5.97 | 0.31 | 2.49 | 1.00 |
| 6 | mm | 16.06 | 0.00 | 0.25 | 0.79 | 0.06 | 0.06 |
| 7 | mm | 16.06 | 6.64 | 42.67 | 0.05 | 15.38 | 3.61 |
| 8 | mm | 16.06 | 0.00 | 0.25 | 0.79 | 0.06 | 0.06 |
| 9 | mm | 16.06 | 0.00 | 0.25 | 0.79 | 0.06 | 0.06 |
| 10 | mm | 16.06 | 0.02 | 0.84 | 0.42 | 0.12 | 0.31 |
| 11 | mm | 16.06 | 0.00 | 0.25 | 0.79 | 0.06 | 0.06 |
| 12 | mm | 16.06 | 0.03 | 0.81 | 0.66 | 0.25 | 0.25 |
| 13 | mm | 16.06 | 0.00 | 0.25 | 0.79 | 0.06 | 0.06 |
| 14 | mm | 16.06 | 0.02 | 0.62 | 0.50 | 0.25 | 0.06 |
| 15 | mm | 16.06 | 0.03 | 1.01 | 0.43 | 0.31 | 0.25 |
| 16 | mm | 16.06 | 0.11 | 1.82 | 0.41 | 0.56 | 0.50 |
| 17 | mm | 16.06 | 2.43 | 18.25 | 0.09 | 8.03 | 1.06 |
| 18 | mm | 16.06 | 0.01 | 0.37 | 0.70 | 0.12 | 0.06 |
| 19 | mm | 16.06 | 0.04 | 1.15 | 0.37 | 0.50 | 0.12 |
| 20 | mm | 16.06 | 0.30 | 3.86 | 0.25 | 1.43 | 0.62 |
| 21 | mm | 16.06 | 0.00 | 0.25 | 0.79 | 0.06 | 0.06 |
| 22 | mm | 16.06 | 1.29 | 9.16 | 0.19 | 3.61 | 0.87 |
| 23 | mm | 16.06 | 0.01 | 0.37 | 0.70 | 0.12 | 0.06 |
| 24 | mm | 16.06 | 0.02 | 0.51 | 0.74 | 0.12 | 0.19 |
| 25 | mm | 16.06 | 0.14 | 1.89 | 0.49 | 0.68 | 0.44 |
| 26 | mm | 16.06 | 1.00 | 8.81 | 0.16 | 3.92 | 0.68 |

**Appendix Table 21** (Continued)

| # | Scale Units | Scale Factor | Area | Perimeter | Circularity | Height | Width |
|---|---|---|---|---|---|---|---|
| 27 | mm | 16.06 | 0.00 | 0.25 | 0.79 | 0.06 | 0.06 |
| 28 | mm | 16.06 | 0.49 | 5.20 | 0.23 | 2.24 | 0.50 |
| 29 | mm | 16.06 | 0.01 | 0.37 | 0.70 | 0.12 | 0.06 |
| 30 | mm | 16.06 | 0.00 | 0.25 | 0.79 | 0.06 | 0.06 |
| 31 | mm | 16.06 | 0.00 | 0.25 | 0.79 | 0.06 | 0.06 |
| 32 | mm | 16.06 | 0.02 | 0.75 | 0.44 | 0.31 | 0.06 |
| 33 | mm | 16.06 | 0.01 | 0.50 | 0.59 | 0.19 | 0.06 |
| 34 | mm | 16.06 | 0.01 | 0.37 | 0.70 | 0.12 | 0.06 |
| 35 | mm | 16.06 | 0.02 | 0.75 | 0.44 | 0.31 | 0.06 |
| 36 | mm | 16.06 | 0.00 | 0.25 | 0.79 | 0.06 | 0.06 |
| 37 | mm | 16.06 | 0.17 | 2.82 | 0.28 | 1.06 | 0.44 |
| 38 | mm | 16.06 | 0.01 | 0.37 | 0.70 | 0.12 | 0.06 |
| 39 | mm | 16.06 | 0.16 | 2.94 | 0.23 | 1.25 | 0.37 |
| 40 | mm | 16.06 | 0.06 | 1.52 | 0.32 | 0.44 | 0.50 |
| 41 | mm | 16.06 | 0.01 | 0.37 | 0.70 | 0.12 | 0.06 |
| 42 | mm | 16.06 | 0.00 | 0.25 | 0.79 | 0.06 | 0.06 |
| 43 | mm | 16.06 | 0.02 | 0.64 | 0.72 | 0.25 | 0.12 |
| 44 | mm | 16.06 | 0.74 | 6.11 | 0.25 | 2.30 | 1.06 |
| 45 | mm | 16.06 | 0.00 | 0.25 | 0.79 | 0.06 | 0.06 |
| 46 | mm | 16.06 | 0.01 | 0.50 | 0.59 | 0.19 | 0.06 |
| 47 | mm | 16.06 | 0.00 | 0.25 | 0.79 | 0.06 | 0.06 |
| 48 | mm | 16.06 | 0.93 | 6.27 | 0.30 | 2.55 | 1.00 |
| 49 | mm | 16.06 | 0.00 | 0.25 | 0.79 | 0.06 | 0.06 |
| 50 | mm | 16.06 | 0.00 | 0.25 | 0.79 | 0.06 | 0.06 |
| 51 | mm | 16.06 | 2.00 | 15.46 | 0.11 | 5.54 | 1.31 |
| 52 | mm | 16.06 | 0.01 | 0.50 | 0.59 | 0.19 | 0.06 |

**Appendix Table 21** (Continued)

| # | Scale Units | Scale Factor | Area | Perimeter | Circularity | Height | Width |
|---|---|---|---|---|---|---|---|
| 53 | mm | 16.06 | 0.03 | 1.25 | 0.28 | 0.56 | 0.06 |
| 54 | mm | 16.06 | 0.00 | 0.25 | 0.79 | 0.06 | 0.06 |
| 55 | mm | 16.06 | 0.01 | 0.37 | 0.70 | 0.12 | 0.06 |
| 56 | mm | 16.06 | 0.00 | 0.25 | 0.79 | 0.06 | 0.06 |
| 57 | mm | 16.06 | 0.00 | 0.25 | 0.79 | 0.06 | 0.06 |
| 58 | mm | 16.06 | 0.00 | 0.25 | 0.79 | 0.06 | 0.06 |
| 59 | mm | 16.06 | 0.14 | 1.91 | 0.49 | 0.62 | 0.50 |
| 60 | mm | 16.06 | 0.85 | 9.05 | 0.13 | 3.74 | 0.87 |
| 61 | mm | 16.06 | 0.01 | 0.37 | 0.70 | 0.12 | 0.06 |
| 62 | mm | 16.06 | 0.31 | 6.45 | 0.09 | 2.74 | 1.00 |
| 63 | mm | 16.06 | 0.10 | 2.11 | 0.30 | 0.81 | 0.37 |
| 64 | mm | 16.06 | 0.00 | 0.25 | 0.79 | 0.06 | 0.06 |
| 65 | mm | 16.06 | 0.00 | 0.25 | 0.79 | 0.06 | 0.06 |
| 66 | mm | 16.06 | 0.10 | 1.98 | 0.32 | 0.81 | 0.37 |
| 67 | mm | 16.06 | 0.00 | 0.25 | 0.79 | 0.06 | 0.06 |
| 68 | mm | 16.06 | 0.11 | 1.95 | 0.36 | 0.62 | 0.56 |
| 69 | mm | 16.06 | 0.00 | 0.25 | 0.79 | 0.06 | 0.06 |
| 70 | mm | 16.06 | 0.33 | 2.59 | 0.63 | 0.93 | 0.56 |
| 71 | mm | 16.06 | 1.06 | 7.60 | 0.23 | 3.24 | 0.81 |
| 72 | mm | 16.06 | 0.08 | 1.57 | 0.39 | 0.56 | 0.44 |
| 73 | mm | 16.06 | 0.19 | 1.84 | 0.72 | 0.75 | 0.37 |
| 74 | mm | 16.06 | 1.03 | 9.84 | 0.13 | 3.98 | 1.49 |
| 75 | mm | 16.06 | 0.01 | 0.50 | 0.59 | 0.19 | 0.06 |
| 76 | mm | 16.06 | 0.00 | 0.25 | 0.79 | 0.06 | 0.06 |
| 77 | mm | 16.06 | 0.78 | 9.19 | 0.12 | 4.11 | 0.68 |
| 78 | mm | 16.06 | 0.07 | 1.77 | 0.29 | 0.68 | 0.19 |

**Appendix Table 21** (Continued)

| # | Scale Units | Scale Factor | Area | Perimeter | Circularity | Height | Width |
|---|---|---|---|---|---|---|---|
| 79 | mm | 16.06 | 0.02 | 0.71 | 0.58 | 0.25 | 0.12 |
| 80 | mm | 16.06 | 0.00 | 0.25 | 0.79 | 0.06 | 0.06 |
| 81 | mm | 16.06 | 0.11 | 2.26 | 0.28 | 1.00 | 0.19 |
| 82 | mm | 16.06 | 0.05 | 1.08 | 0.58 | 0.37 | 0.25 |
| 83 | mm | 16.06 | 0.30 | 4.64 | 0.18 | 1.74 | 1.06 |
| 84 | mm | 16.06 | 0.03 | 1.12 | 0.31 | 0.50 | 0.06 |
| 85 | mm | 16.06 | 2.90 | 17.85 | 0.11 | 7.47 | 1.74 |
| 86 | mm | 16.06 | 1.93 | 17.94 | 0.08 | 6.72 | 2.74 |
| 87 | mm | 16.06 | 0.01 | 0.37 | 0.70 | 0.06 | 0.12 |
| 88 | mm | 16.06 | 0.26 | 4.65 | 0.15 | 2.12 | 0.31 |
| 89 | mm | 16.06 | 0.00 | 0.25 | 0.79 | 0.06 | 0.06 |
| 90 | mm | 16.06 | 0.01 | 0.37 | 0.70 | 0.12 | 0.06 |
| 91 | mm | 16.06 | 4.81 | 25.66 | 0.09 | 10.40 | 2.43 |
| 92 | mm | 16.06 | 0.00 | 0.25 | 0.79 | 0.06 | 0.06 |
| | Total Area | | 72.39 | | | | |

**Appendix Table 22** Crack area calculation for specimen M30PVA2.

| # | Scale Units | Scale Factor | Area | Perimeter | Circularity | Height | Width |
|---|---|---|---|---|---|---|---|
| 1 | mm | 18.18 | 16.97 | 100.85 | 0.02 | 4.73 | 35.81 |
| 2 | mm | 18.18 | 6.08 | 30.36 | 0.08 | 2.48 | 11.50 |
| 3 | mm | 18.18 | 2.27 | 11.47 | 0.22 | 1.71 | 4.51 |
| 4 | mm | 18.18 | 0.00 | 0.22 | 0.79 | 0.06 | 0.06 |
| 5 | mm | 18.18 | 3.65 | 18.12 | 0.14 | 2.59 | 6.71 |
| 6 | mm | 18.18 | 0.00 | 0.22 | 0.79 | 0.06 | 0.06 |
| 7 | mm | 18.18 | 0.01 | 0.44 | 0.79 | 0.11 | 0.11 |
| 8 | mm | 18.18 | 0.54 | 4.38 | 0.36 | 0.72 | 1.54 |
| 9 | mm | 18.18 | 1.46 | 9.04 | 0.22 | 1.87 | 3.36 |
| 10 | mm | 18.18 | 0.09 | 1.19 | 0.78 | 0.39 | 0.33 |
| 11 | mm | 18.18 | 1.28 | 7.68 | 0.27 | 0.94 | 2.81 |
| 12 | mm | 18.18 | 0.16 | 3.08 | 0.21 | 0.44 | 1.21 |
| 13 | mm | 18.18 | 0.17 | 2.30 | 0.39 | 0.66 | 0.50 |
| 14 | mm | 18.18 | 0.00 | 0.22 | 0.79 | 0.06 | 0.06 |
| 15 | mm | 18.18 | 0.05 | 1.11 | 0.50 | 0.33 | 0.39 |
| 16 | mm | 18.18 | 0.00 | 0.22 | 0.79 | 0.06 | 0.06 |
| 17 | mm | 18.18 | 0.00 | 0.22 | 0.79 | 0.06 | 0.06 |
| 18 | mm | 18.18 | 0.00 | 0.22 | 0.79 | 0.06 | 0.06 |
| 19 | mm | 18.18 | 1.01 | 7.22 | 0.24 | 0.99 | 2.86 |
| 20 | mm | 18.18 | 0.02 | 0.53 | 0.67 | 0.17 | 0.17 |
| 21 | mm | 18.18 | 0.17 | 2.60 | 0.31 | 0.28 | 1.16 |
| 22 | mm | 18.18 | 16.97 | 100.85 | 0.02 | 4.73 | 35.81 |
| 23 | mm | 18.18 | 6.08 | 30.36 | 0.08 | 2.48 | 11.50 |
| 24 | mm | 18.18 | 16.97 | 100.85 | 0.02 | 4.73 | 35.81 |
| 25 | mm | 18.18 | 6.08 | 30.36 | 0.08 | 2.48 | 11.50 |
| 26 | mm | 18.18 | 2.27 | 11.47 | 0.22 | 1.71 | 4.51 |

**Appendix Table 22** (Continued)

| # | Scale Units | Scale Factor | Area | Perimeter | Circularity | Height | Width |
|---|---|---|---|---|---|---|---|
| 27 | mm | 18.18 | 2.27 | 11.47 | 0.22 | 1.71 | 4.51 |
| 28 | mm | 18.18 | 0.00 | 0.22 | 0.79 | 0.06 | 0.06 |
| 29 | mm | 18.18 | 3.65 | 18.12 | 0.14 | 2.59 | 6.71 |
| 30 | mm | 18.18 | 0.00 | 0.22 | 0.79 | 0.06 | 0.06 |
| 31 | mm | 18.18 | 0.01 | 0.44 | 0.79 | 0.11 | 0.11 |
| 32 | mm | 18.18 | 0.54 | 4.38 | 0.36 | 0.72 | 1.54 |
| 33 | mm | 18.18 | 1.46 | 9.04 | 0.22 | 1.87 | 3.36 |
| 34 | mm | 18.18 | 0.09 | 1.19 | 0.78 | 0.39 | 0.33 |
| 35 | mm | 18.18 | 1.28 | 7.68 | 0.27 | 0.94 | 2.81 |
| 36 | mm | 18.18 | 0.16 | 3.08 | 0.21 | 0.44 | 1.21 |
| 37 | mm | 18.18 | 0.17 | 2.30 | 0.39 | 0.66 | 0.50 |
| 38 | mm | 18.18 | 0.00 | 0.22 | 0.79 | 0.06 | 0.06 |
| 39 | mm | 18.18 | 0.05 | 1.11 | 0.50 | 0.33 | 0.39 |
| 40 | mm | 18.18 | 0.00 | 0.22 | 0.79 | 0.06 | 0.06 |
| 41 | mm | 18.18 | 0.00 | 0.22 | 0.79 | 0.06 | 0.06 |
| 42 | mm | 18.18 | 0.00 | 0.22 | 0.79 | 0.06 | 0.06 |
| 43 | mm | 18.18 | 1.01 | 7.22 | 0.24 | 0.99 | 2.86 |
| 44 | mm | 18.18 | 0.02 | 0.53 | 0.67 | 0.17 | 0.17 |
| 45 | mm | 18.18 | 0.17 | 2.60 | 0.31 | 0.28 | 1.16 |
| | Total Area | | 67.87 | | | | |

**Appendix Table 23** Crack area calculation for specimen M30PVA3.

| # | Scale Units | Scale Factor | Area | Perimeter | Circularity | Height | Width |
|---|---|---|---|---|---|---|---|
| 1 | mm | 19.40 | 3.76 | 47.53 | 0.02 | 5.67 | 23.92 |
| 2 | mm | 19.40 | 0.93 | 11.74 | 0.08 | 1.60 | 4.85 |
| 3 | mm | 19.40 | 0.18 | 2.07 | 0.52 | 0.41 | 0.82 |
| 4 | mm | 19.40 | 0.87 | 9.88 | 0.11 | 1.29 | 4.18 |
| 5 | mm | 19.40 | 0.46 | 5.10 | 0.22 | 0.98 | 1.86 |
| 6 | mm | 19.40 | 0.01 | 0.41 | 0.59 | 0.15 | 0.05 |
| 7 | mm | 19.40 | 0.81 | 9.57 | 0.11 | 0.77 | 3.81 |
| 8 | mm | 19.40 | 0.24 | 3.74 | 0.22 | 0.62 | 1.44 |
| 9 | mm | 19.40 | 0.01 | 0.37 | 0.74 | 0.10 | 0.10 |
| 10 | mm | 19.40 | 0.24 | 3.81 | 0.21 | 0.67 | 1.55 |
| 11 | mm | 19.40 | 0.01 | 0.41 | 0.59 | 0.15 | 0.05 |
| 12 | mm | 19.40 | 0.01 | 0.42 | 0.74 | 0.15 | 0.10 |
| 13 | mm | 19.40 | 3.59 | 47.91 | 0.02 | 10.93 | 35.41 |
| 14 | mm | 19.40 | 1.41 | 20.22 | 0.04 | 0.93 | 9.12 |
| 15 | mm | 19.40 | 0.54 | 8.86 | 0.09 | 1.39 | 3.71 |
| 16 | mm | 19.40 | 0.41 | 4.44 | 0.26 | 0.31 | 2.01 |
| 17 | mm | 19.40 | 0.41 | 4.94 | 0.21 | 0.93 | 1.96 |
| 18 | mm | 19.40 | 0.14 | 2.18 | 0.36 | 0.41 | 0.88 |
| 19 | mm | 19.40 | 0.68 | 7.26 | 0.16 | 0.98 | 2.99 |
| 20 | mm | 19.40 | 1.55 | 43.66 | 0.01 | 5.46 | 26.55 |
| 21 | mm | 19.40 | 0.75 | 22.57 | 0.02 | 3.35 | 9.33 |
| 22 | mm | 19.40 | 0.18 | 4.04 | 0.14 | 0.31 | 1.86 |
| 23 | mm | 19.40 | 0.62 | 17.05 | 0.03 | 2.58 | 6.91 |
| Total Area | | | 17.81 | | | | |

**Appendix Table 24** Crack area calculation for specimen M30SF1.

| # | Scale Units | Scale Factor | Area | Perimeter | Circularity | Height | Width |
|---|---|---|---|---|---|---|---|
| 1 | mm | 31.80 | 74.76 | 453.35 | 0.00 | 29.62 | 104.65 |
| 2 | mm | 31.80 | 0.00 | 0.13 | 0.79 | 0.03 | 0.03 |
| 3 | mm | 31.80 | 0.00 | 0.31 | 0.50 | 0.13 | 0.03 |
| 4 | mm | 31.80 | 0.00 | 0.25 | 0.79 | 0.06 | 0.06 |
| 5 | mm | 31.80 | 0.97 | 13.09 | 0.07 | 4.50 | 2.30 |
| 6 | mm | 31.80 | 0.16 | 3.77 | 0.14 | 1.13 | 1.19 |
| 7 | mm | 31.80 | 0.04 | 1.20 | 0.37 | 0.25 | 0.44 |
| 8 | mm | 31.80 | 0.16 | 2.44 | 0.33 | 0.25 | 1.04 |
| 9 | mm | 31.80 | 0.27 | 3.48 | 0.28 | 0.35 | 1.42 |
| 10 | mm | 31.80 | 0.10 | 1.43 | 0.61 | 0.22 | 0.53 |
| 11 | mm | 31.80 | 0.08 | 2.12 | 0.22 | 0.28 | 0.72 |
| 12 | mm | 31.80 | 0.02 | 0.73 | 0.41 | 0.16 | 0.25 |
| 13 | mm | 31.80 | 0.62 | 7.31 | 0.15 | 0.60 | 2.92 |
| 14 | mm | 31.80 | 0.00 | 0.13 | 0.79 | 0.03 | 0.03 |
| 15 | mm | 31.80 | 0.01 | 0.35 | 0.62 | 0.09 | 0.13 |
| 16 | mm | 31.80 | 0.01 | 0.39 | 0.72 | 0.13 | 0.09 |
| 17 | mm | 31.80 | 0.00 | 0.13 | 0.79 | 0.03 | 0.03 |
| 18 | mm | 31.80 | 0.00 | 0.13 | 0.79 | 0.03 | 0.03 |
| 19 | mm | 31.80 | 0.00 | 0.22 | 0.74 | 0.06 | 0.06 |
| 20 | mm | 31.80 | 0.00 | 0.13 | 0.79 | 0.03 | 0.03 |
| 21 | mm | 31.80 | 0.00 | 0.13 | 0.79 | 0.03 | 0.03 |
| 22 | mm | 31.80 | 2.66 | 15.01 | 0.15 | 1.51 | 6.26 |
| 23 | mm | 31.80 | 0.90 | 7.59 | 0.20 | 0.94 | 3.05 |
| 24 | mm | 31.80 | 74.76 | 453.35 | 0.00 | 29.62 | 104.65 |
| 25 | mm | 31.80 | 0.00 | 0.13 | 0.79 | 0.03 | 0.03 |
| 26 | mm | 31.80 | 0.00 | 0.31 | 0.50 | 0.13 | 0.03 |

**Appendix Table 24** (Continued).

| # | Scale Units | Scale Factor | Area | Perimeter | Circularity | Height | Width |
|---|---|---|---|---|---|---|---|
| 27 | mm | 31.80 | 4.34 | 24.63 | 0.09 | 4.53 | 8.71 |
| 28 | mm | 31.80 | 5.82 | 24.43 | 0.12 | 1.54 | 9.69 |
| 29 | mm | 31.80 | 0.00 | 0.13 | 0.79 | 0.03 | 0.03 |
| 30 | mm | 31.80 | 1.14 | 8.70 | 0.19 | 0.82 | 3.62 |
| 31 | mm | 31.80 | 0.00 | 0.13 | 0.79 | 0.03 | 0.03 |
| 32 | mm | 31.80 | 0.00 | 0.19 | 0.70 | 0.03 | 0.06 |
| 33 | mm | 31.80 | 0.00 | 0.13 | 0.79 | 0.03 | 0.03 |
| 34 | mm | 31.80 | 11.06 | 41.89 | 0.08 | 3.27 | 17.52 |
| 35 | mm | 31.80 | 0.00 | 0.13 | 0.79 | 0.03 | 0.03 |
| 36 | mm | 31.80 | 0.00 | 0.26 | 0.74 | 0.09 | 0.06 |
| 37 | mm | 31.80 | 0.03 | 1.21 | 0.27 | 0.47 | 0.25 |
| 38 | mm | 31.80 | 14.68 | 59.21 | 0.05 | 2.45 | 24.25 |
| 39 | mm | 31.80 | 0.00 | 0.13 | 0.79 | 0.03 | 0.03 |
| 40 | mm | 31.80 | 0.01 | 0.36 | 0.88 | 0.09 | 0.13 |
| 41 | mm | 31.80 | 0.00 | 0.13 | 0.79 | 0.03 | 0.03 |
| 42 | mm | 31.80 | 0.60 | 7.71 | 0.13 | 0.60 | 3.21 |
| 43 | mm | 31.80 | 0.05 | 1.30 | 0.39 | 0.31 | 0.50 |
| 44 | mm | 31.80 | 0.00 | 0.22 | 0.74 | 0.06 | 0.06 |
| 45 | mm | 31.80 | 0.00 | 0.30 | 0.57 | 0.06 | 0.09 |
| 46 | mm | 31.80 | 0.01 | 0.40 | 0.77 | 0.09 | 0.16 |
| 47 | mm | 31.80 | 0.03 | 1.38 | 0.22 | 0.31 | 0.50 |
| 48 | mm | 31.80 | 0.00 | 0.13 | 0.79 | 0.03 | 0.03 |
| 49 | mm | 31.80 | 0.00 | 0.13 | 0.79 | 0.03 | 0.03 |
| 50 | mm | 31.80 | 0.14 | 3.17 | 0.18 | 0.69 | 1.23 |
| 51 | mm | 31.80 | 1.88 | 21.58 | 0.05 | 3.36 | 9.09 |
| 52 | mm | 31.80 | 0.01 | 0.35 | 0.62 | 0.09 | 0.13 |

**Appendix Table 24** (Continued).

| # | Scale Units | Scale Factor | Area | Perimeter | Circularity | Height | Width |
|---|---|---|---|---|---|---|---|
| 53 | mm | 31.80 | 8.25 | 30.50 | 0.11 | 2.55 | 11.13 |
| 54 | mm | 31.80 | 0.18 | 2.34 | 0.41 | 0.31 | 0.91 |
| 55 | mm | 31.80 | 0.00 | 0.22 | 0.74 | 0.06 | 0.06 |
| 56 | mm | 31.80 | 9.52 | 54.17 | 0.04 | 4.28 | 18.74 |
| 57 | mm | 31.80 | 0.00 | 0.13 | 0.79 | 0.03 | 0.03 |
| 58 | mm | 31.80 | 0.01 | 0.40 | 0.61 | 0.13 | 0.09 |
| 59 | mm | 31.80 | 0.00 | 0.13 | 0.79 | 0.03 | 0.03 |
| 60 | mm | 31.80 | 0.01 | 0.49 | 0.77 | 0.16 | 0.13 |
| 61 | mm | 31.80 | 0.00 | 0.13 | 0.79 | 0.03 | 0.03 |
| 62 | mm | 31.80 | 0.00 | 0.25 | 0.59 | 0.03 | 0.09 |
| 63 | mm | 31.80 | 0.00 | 0.13 | 0.79 | 0.03 | 0.03 |
| 64 | mm | 31.80 | 0.00 | 0.13 | 0.79 | 0.03 | 0.03 |
| 65 | mm | 31.80 | 0.00 | 0.25 | 0.79 | 0.06 | 0.06 |
| 66 | mm | 31.80 | 0.00 | 0.13 | 0.79 | 0.03 | 0.03 |
| 67 | mm | 31.80 | 0.01 | 0.66 | 0.42 | 0.13 | 0.25 |
| 68 | mm | 31.80 | 0.01 | 0.33 | 0.68 | 0.09 | 0.09 |
| 69 | mm | 31.80 | 0.01 | 0.42 | 0.85 | 0.16 | 0.13 |
| 70 | mm | 31.80 | 0.13 | 1.83 | 0.49 | 0.57 | 0.57 |
| 71 | mm | 31.80 | 2.60 | 18.92 | 0.09 | 1.35 | 7.08 |
| 72 | mm | 31.80 | 2.20 | 14.44 | 0.13 | 2.08 | 5.69 |
| 73 | mm | 31.80 | 0.00 | 0.13 | 0.79 | 0.03 | 0.03 |
| 74 | mm | 31.80 | 0.01 | 0.60 | 0.48 | 0.13 | 0.22 |
| 75 | mm | 31.80 | 0.80 | 5.46 | 0.34 | 0.60 | 2.14 |
| 76 | mm | 31.80 | 1.26 | 17.52 | 0.05 | 1.64 | 7.08 |
| 77 | mm | 31.80 | 0.00 | 0.13 | 0.79 | 0.03 | 0.03 |
| 78 | mm | 31.80 | 0.93 | 9.96 | 0.12 | 1.60 | 4.21 |

**Appendix Table 24** (Continued).

| # | Scale Units | Scale Factor | Area | Perimeter | Circularity | Height | Width |
|---|---|---|---|---|---|---|---|
| 80 | mm | 31.80 | 0.17 | 3.83 | 0.15 | 0.28 | 1.76 |
| 81 | mm | 31.80 | 0.22 | 3.56 | 0.22 | 0.63 | 1.51 |
| 82 | mm | 31.80 | 0.00 | 0.19 | 0.70 | 0.03 | 0.06 |
| 83 | mm | 31.80 | 0.00 | 0.13 | 0.79 | 0.03 | 0.03 |
| 84 | mm | 31.80 | 0.00 | 0.19 | 0.70 | 0.03 | 0.06 |
| 85 | mm | 31.80 | 0.00 | 0.19 | 0.70 | 0.03 | 0.06 |
| 86 | mm | 31.80 | 0.00 | 0.13 | 0.79 | 0.03 | 0.03 |
| 87 | mm | 31.80 | 0.00 | 0.25 | 0.59 | 0.03 | 0.09 |
| 88 | mm | 31.80 | 0.00 | 0.19 | 0.70 | 0.06 | 0.03 |
| 89 | mm | 31.80 | 0.00 | 0.13 | 0.79 | 0.03 | 0.03 |
| 90 | mm | 31.80 | 0.00 | 0.13 | 0.79 | 0.03 | 0.03 |
| 91 | mm | 31.80 | 0.00 | 0.13 | 0.79 | 0.03 | 0.03 |
| 92 | mm | 31.80 | 2.38 | 20.98 | 0.07 | 1.95 | 9.31 |
| 93 | mm | 31.80 | 0.00 | 0.13 | 0.79 | 0.03 | 0.03 |
| 94 | mm | 31.80 | 0.00 | 0.13 | 0.79 | 0.03 | 0.03 |
| 95 | mm | 31.80 | 0.00 | 0.13 | 0.79 | 0.03 | 0.03 |
| 96 | mm | 31.80 | 0.00 | 0.13 | 0.79 | 0.03 | 0.03 |
| 97 | mm | 31.80 | 0.00 | 0.19 | 0.70 | 0.03 | 0.06 |
| 98 | mm | 31.80 | 0.02 | 1.07 | 0.17 | 0.03 | 0.50 |
| 99 | mm | 31.80 | 0.00 | 0.36 | 0.48 | 0.06 | 0.13 |
| 100 | mm | 31.80 | 0.00 | 0.13 | 0.79 | 0.03 | 0.03 |
| 101 | mm | 31.80 | 0.00 | 0.13 | 0.79 | 0.03 | 0.03 |
| Total Area | | | 149.53 | | | | |

**Appendix Table 25** Crack area calculation for specimen M30SF2.

| # | Scale Units | Scale Factor | Area | Perimeter | Circularity | Height | Width |
|---|---|---|---|---|---|---|---|
| 1 | mm | 22.30 | 70.54 | 309.83 | 0.01 | 22.87 | 105.34 |
| 2 | mm | 22.30 | 0.01 | 0.36 | 0.59 | 0.04 | 0.13 |
| 3 | mm | 22.30 | 21.20 | 82.39 | 0.04 | 10.13 | 28.61 |
| 4 | mm | 22.30 | 0.01 | 0.36 | 0.59 | 0.04 | 0.13 |
| 5 | mm | 22.30 | 0.01 | 0.56 | 0.56 | 0.09 | 0.22 |
| 6 | mm | 22.30 | 28.04 | 104.67 | 0.03 | 6.37 | 44.17 |
| 7 | mm | 22.30 | 0.00 | 0.27 | 0.70 | 0.04 | 0.09 |
| 8 | mm | 22.30 | 0.00 | 0.27 | 0.70 | 0.04 | 0.09 |
| 9 | mm | 22.30 | 0.01 | 0.54 | 0.44 | 0.04 | 0.22 |
| 10 | mm | 22.30 | 0.00 | 0.18 | 0.79 | 0.04 | 0.04 |
| 11 | mm | 22.30 | 0.00 | 0.27 | 0.70 | 0.09 | 0.04 |
| 12 | mm | 22.30 | 0.00 | 0.18 | 0.79 | 0.04 | 0.04 |
| 13 | mm | 22.30 | 0.01 | 0.32 | 0.74 | 0.09 | 0.09 |
| 14 | mm | 22.30 | 0.00 | 0.27 | 0.70 | 0.09 | 0.04 |
| 15 | mm | 22.30 | 0.00 | 0.18 | 0.79 | 0.04 | 0.04 |
| 16 | mm | 22.30 | 0.00 | 0.27 | 0.70 | 0.04 | 0.09 |
| 17 | mm | 22.30 | 0.00 | 0.18 | 0.79 | 0.04 | 0.04 |
| 18 | mm | 22.30 | 0.00 | 0.27 | 0.70 | 0.04 | 0.09 |
| 19 | mm | 22.30 | 0.00 | 0.18 | 0.79 | 0.04 | 0.04 |
| 20 | mm | 22.30 | 0.00 | 0.27 | 0.70 | 0.04 | 0.09 |
| 21 | mm | 22.30 | 0.00 | 0.18 | 0.79 | 0.04 | 0.04 |
| 22 | mm | 22.30 | 0.00 | 0.18 | 0.79 | 0.04 | 0.04 |
| 23 | mm | 22.30 | 0.01 | 0.37 | 0.74 | 0.09 | 0.13 |
| 24 | mm | 22.30 | 0.00 | 0.18 | 0.79 | 0.04 | 0.04 |
| 25 | mm | 22.30 | 0.00 | 0.18 | 0.79 | 0.04 | 0.04 |
| 26 | mm | 22.30 | 7.37 | 36.48 | 0.07 | 2.47 | 15.78 |

**Appendix Table 25** (Continued).

| # | Scale Units | Scale Factor | Area | Perimeter | Circularity | Height | Width |
|---|---|---|---|---|---|---|---|
| 27 | mm | 22.30 | 0.00 | 0.27 | 0.70 | 0.04 | 0.09 |
| 28 | mm | 22.30 | 0.01 | 0.36 | 0.59 | 0.04 | 0.13 |
| 29 | mm | 22.30 | 0.00 | 0.27 | 0.70 | 0.04 | 0.09 |
| 30 | mm | 22.30 | 0.05 | 1.49 | 0.30 | 0.27 | 0.63 |
| 31 | mm | 22.30 | 0.00 | 0.27 | 0.70 | 0.04 | 0.09 |
| 32 | mm | 22.30 | 0.00 | 0.18 | 0.79 | 0.04 | 0.04 |
| 33 | mm | 22.30 | 0.01 | 0.36 | 0.59 | 0.04 | 0.13 |
| 34 | mm | 22.30 | 6.25 | 28.83 | 0.09 | 1.57 | 12.69 |
| 35 | mm | 22.30 | 0.00 | 0.18 | 0.79 | 0.04 | 0.04 |
| 36 | mm | 22.30 | 5.23 | 26.44 | 0.09 | 2.51 | 11.93 |
| 37 | mm | 22.30 | 0.19 | 3.43 | 0.20 | 0.49 | 1.39 |
| 38 | mm | 22.30 | 0.01 | 0.54 | 0.44 | 0.04 | 0.22 |
| 39 | mm | 22.30 | 0.05 | 1.19 | 0.41 | 0.22 | 0.45 |
| 40 | mm | 22.30 | 1.85 | 9.93 | 0.24 | 0.81 | 4.39 |
| 41 | mm | 22.30 | 0.01 | 0.32 | 0.74 | 0.09 | 0.09 |
| 42 | mm | 22.30 | 0.00 | 0.18 | 0.79 | 0.04 | 0.04 |
| 43 | mm | 22.30 | 0.00 | 0.18 | 0.79 | 0.04 | 0.04 |
| 44 | mm | 22.30 | 0.00 | 0.18 | 0.79 | 0.04 | 0.04 |
| 45 | mm | 22.30 | 0.12 | 2.66 | 0.22 | 0.54 | 0.99 |
| 46 | mm | 22.30 | 0.00 | 0.27 | 0.70 | 0.04 | 0.09 |
| 47 | mm | 22.30 | 0.01 | 0.54 | 0.62 | 0.13 | 0.18 |
| 48 | mm | 22.30 | 0.00 | 0.27 | 0.70 | 0.09 | 0.04 |
| 49 | mm | 22.30 | 0.00 | 0.18 | 0.79 | 0.04 | 0.04 |
| 50 | mm | 22.30 | 0.00 | 0.27 | 0.70 | 0.04 | 0.09 |
| 51 | mm | 22.30 | 0.00 | 0.18 | 0.79 | 0.04 | 0.04 |
| 52 | mm | 22.30 | 0.00 | 0.27 | 0.70 | 0.04 | 0.09 |

**Appendix Table 25** (Continued).

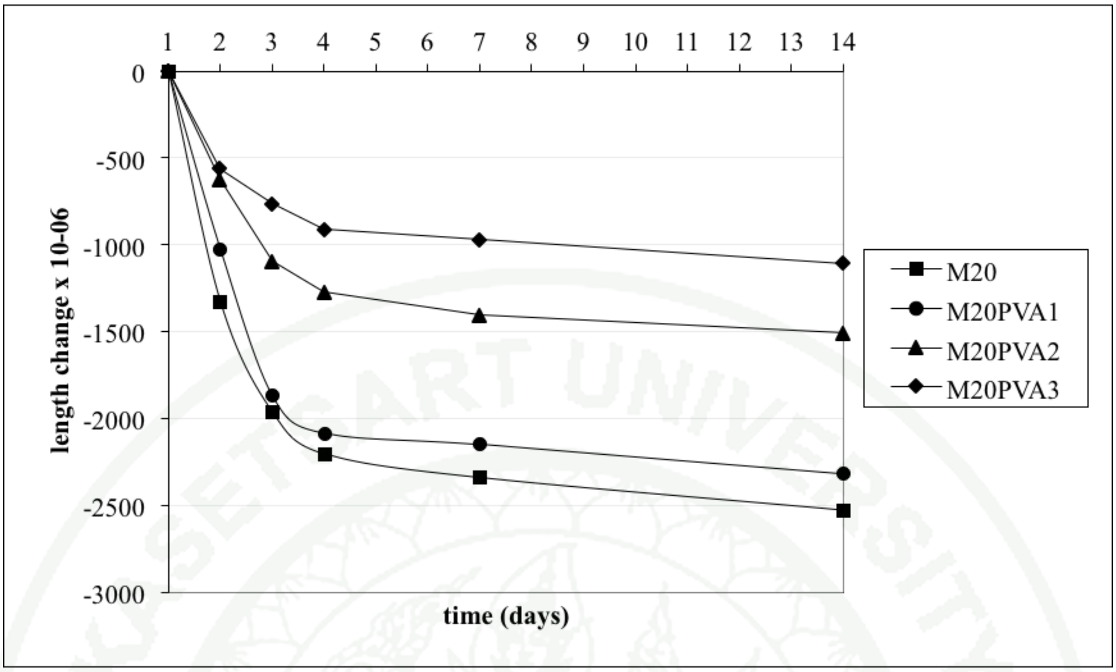
| # | Scale Units | Scale Factor | Area | Perimeter | Circularity | Height | Width |
|---|---|---|---|---|---|---|---|
| 53 | mm | 22.30 | 0.00 | 0.18 | 0.79 | 0.04 | 0.04 |
| 54 | mm | 22.30 | 0.00 | 0.18 | 0.79 | 0.04 | 0.04 |
| 55 | mm | 22.30 | 0.01 | 0.36 | 0.59 | 0.04 | 0.13 |
| 56 | mm | 22.30 | 0.00 | 0.18 | 0.79 | 0.04 | 0.04 |
| 57 | mm | 22.30 | 0.00 | 0.18 | 0.79 | 0.04 | 0.04 |
| | Total Area | | 141.08 | | | | |

**Appendix Table 26** Crack area calculation for specimen M30SF3.

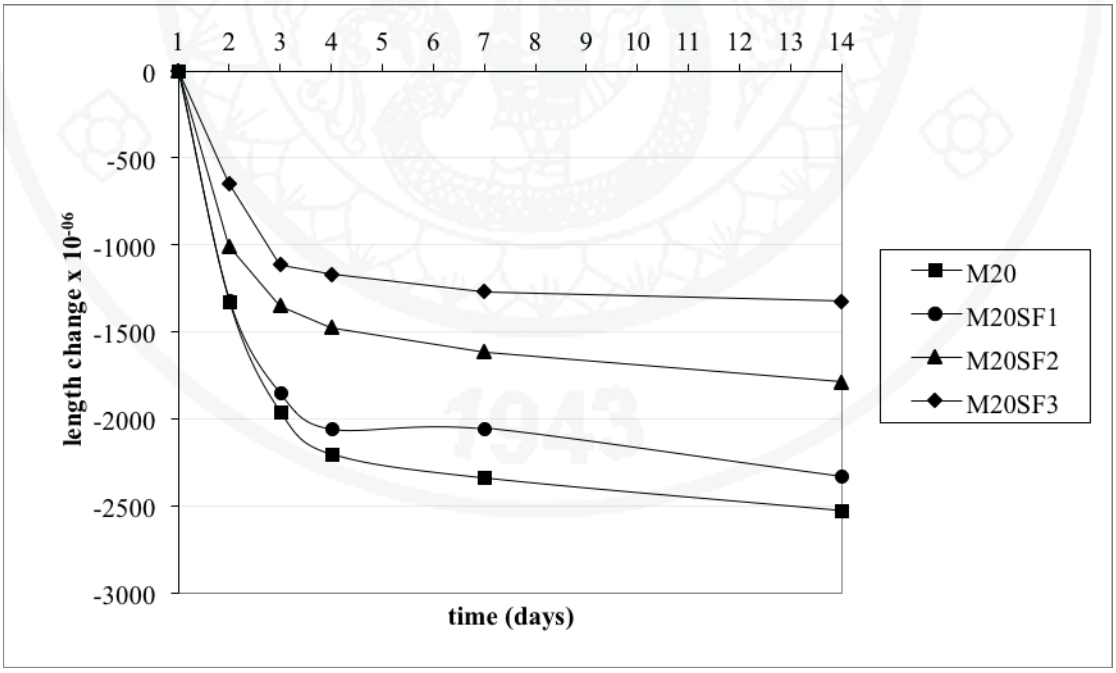
| # | Scale Units | Scale Factor | Area | Perimeter | Circularity | Height | Width |
|---|---|---|---|---|---|---|---|
| 1 | mm | 19.09 | 26.17 | 115.15 | 0.02 | 9.59 | 37.19 |
| 2 | mm | 19.09 | 11.82 | 45.06 | 0.07 | 4.09 | 16.61 |
| 3 | mm | 19.09 | 1.40 | 11.27 | 0.14 | 1.00 | 4.82 |
| 4 | mm | 19.09 | 2.37 | 10.46 | 0.27 | 1.26 | 4.19 |
| 5 | mm | 19.09 | 0.01 | 0.42 | 0.59 | 0.05 | 0.16 |
| 6 | mm | 19.09 | 8.02 | 31.43 | 0.10 | 3.46 | 11.52 |
| 7 | mm | 19.09 | 0.01 | 0.49 | 0.57 | 0.16 | 0.10 |
| 8 | mm | 19.09 | 1.53 | 7.94 | 0.31 | 1.57 | 2.67 |
| 9 | mm | 19.09 | 0.98 | 6.72 | 0.27 | 0.84 | 2.62 |
| 10 | mm | 19.09 | 0.01 | 0.31 | 0.70 | 0.05 | 0.10 |
| 11 | mm | 19.09 | 0.01 | 0.31 | 0.70 | 0.10 | 0.05 |
| 12 | mm | 19.09 | 0.00 | 0.21 | 0.79 | 0.05 | 0.05 |
| 13 | mm | 19.09 | 0.01 | 0.31 | 0.70 | 0.05 | 0.10 |
| 14 | mm | 19.09 | 0.00 | 0.21 | 0.79 | 0.05 | 0.05 |
| 15 | mm | 19.09 | 42.43 | 145.07 | 0.03 | 4.40 | 53.90 |
| 16 | mm | 19.09 | 2.64 | 11.27 | 0.26 | 1.10 | 4.24 |
| 17 | mm | 19.09 | 39.76 | 132.30 | 0.03 | 4.09 | 49.61 |
| 18 | mm | 19.09 | 0.00 | 0.21 | 0.79 | 0.05 | 0.05 |
| 19 | mm | 19.09 | 0.01 | 0.31 | 0.70 | 0.05 | 0.10 |
| 20 | mm | 19.09 | 0.00 | 0.21 | 0.79 | 0.05 | 0.05 |
| 21 | mm | 19.09 | 0.01 | 0.55 | 0.57 | 0.10 | 0.21 |
| 22 | mm | 19.09 | 0.00 | 0.21 | 0.79 | 0.05 | 0.05 |
| 23 | mm | 19.09 | 7.22 | 41.23 | 0.05 | 5.66 | 14.09 |

**Appendix Table 26** (Continued).

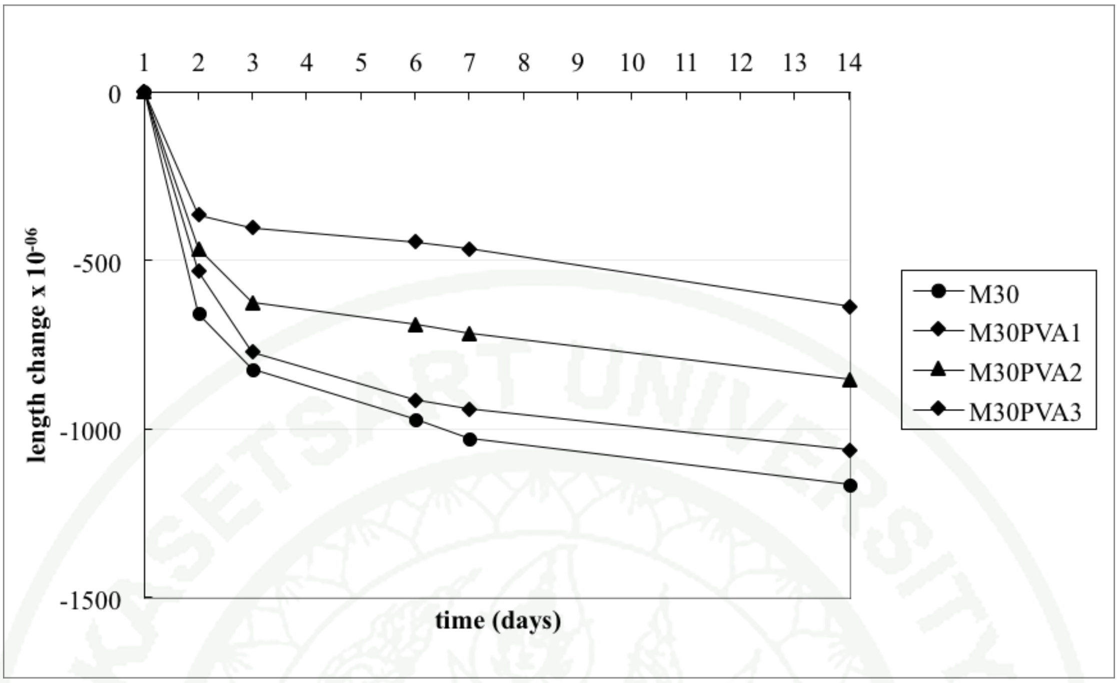
| # | Scale Units | Scale Factor | Area | Perimeter | Circularity | Height | Width |
|---|---|---|---|---|---|---|---|
| 24 | mm | 19.09 | 4.70 | 27.21 | 0.08 | 4.30 | 9.22 |
| 25 | mm | 19.09 | 0.01 | 0.44 | 0.87 | 0.16 | 0.16 |
| 26 | mm | 19.09 | 2.50 | 13.27 | 0.18 | 2.10 | 4.77 |
| 27 | mm | 19.09 | 0.01 | 0.31 | 0.70 | 0.05 | 0.10 |
| | Total Area | | 151.63 | | | | |



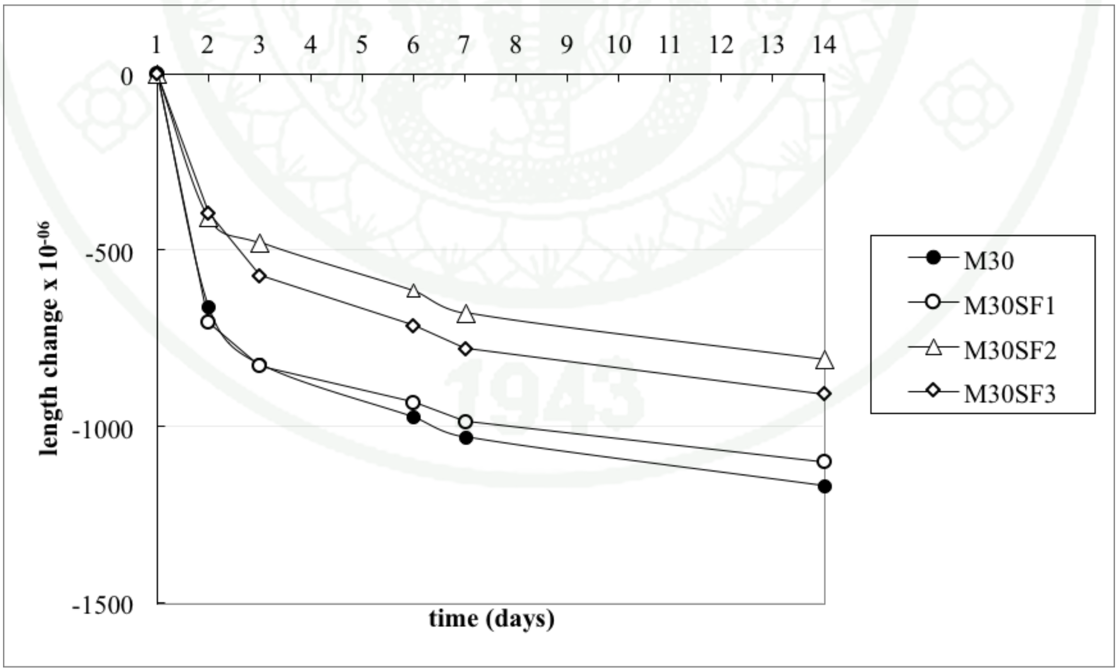

**Appendix Figure 1** Free shrinkage of M20 concrete series with PVA fiber over 14 days



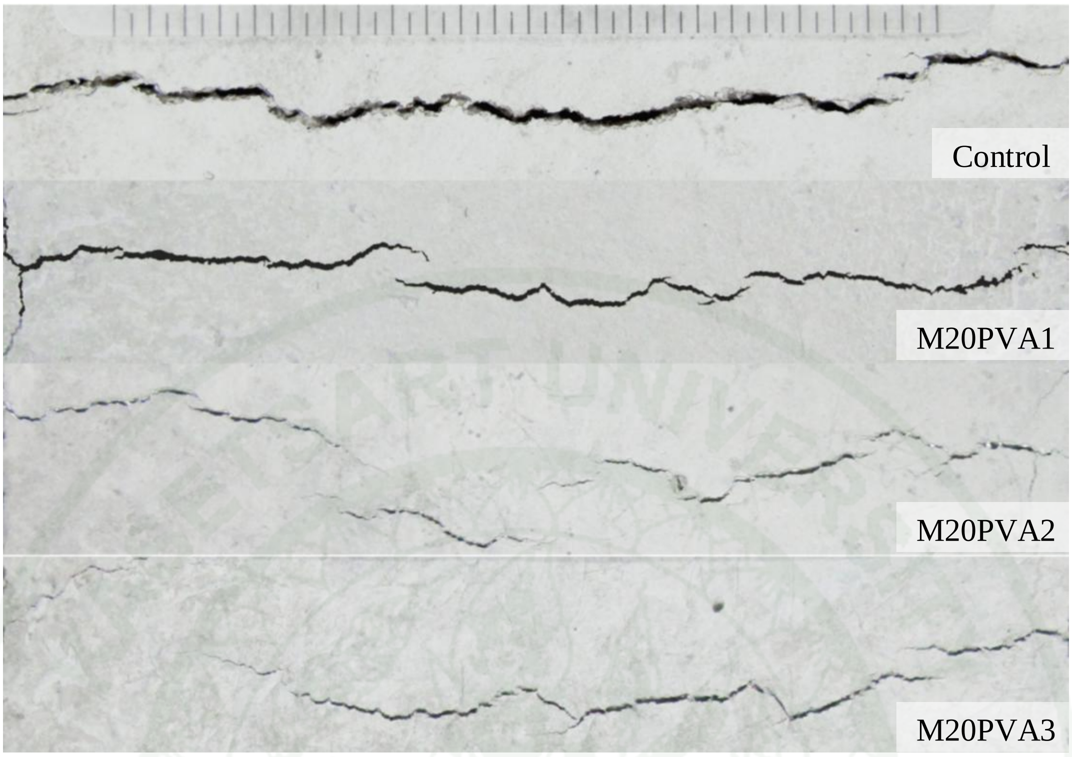

**Appendix Figure 2** Free shrinkage of M20 concrete series with Steel fiber over 14 days



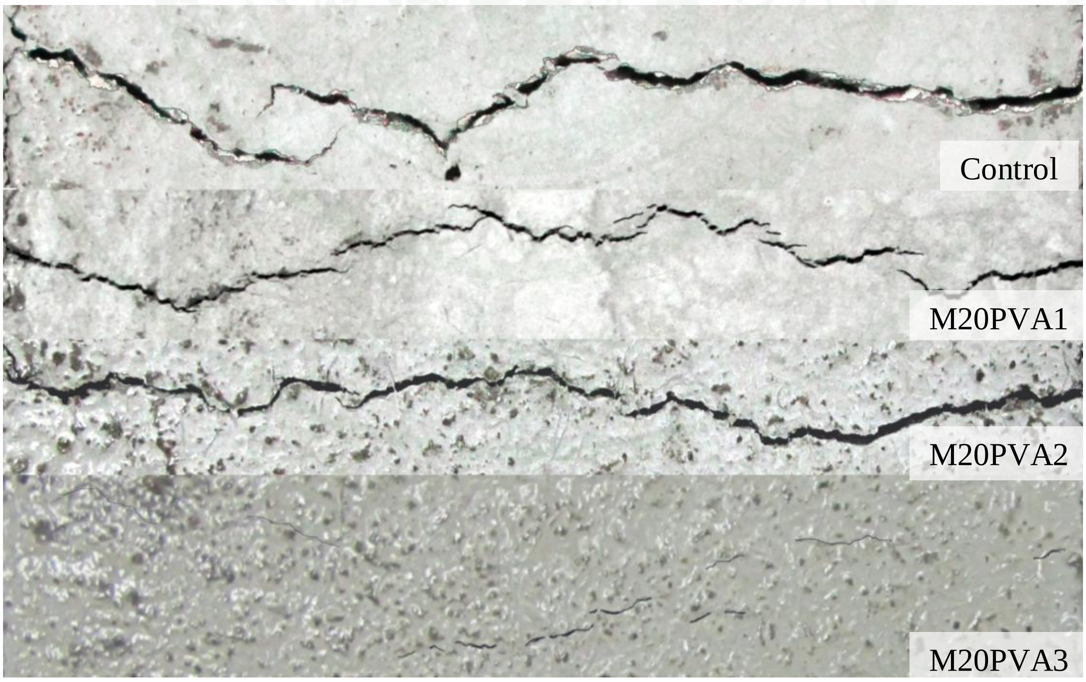

**Appendix Figure 3** Free shrinkage of M30 concrete series with PVA fiber over 14 days



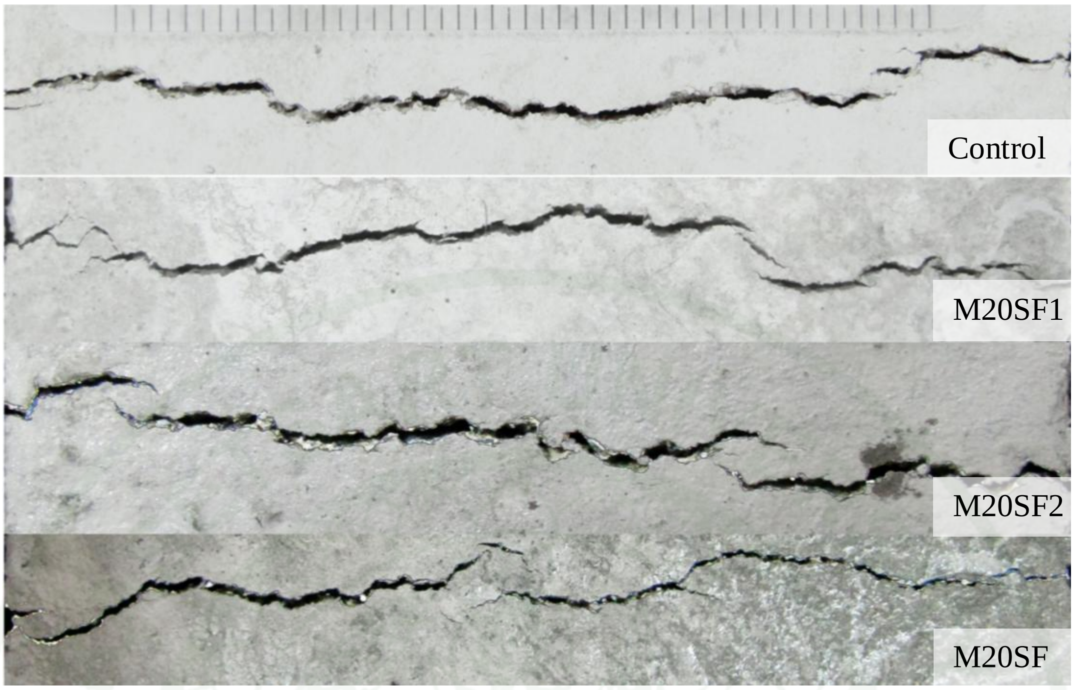

**Appendix Figure 4** Free shrinkage of M30 concrete series with Steel fiber over 14 days



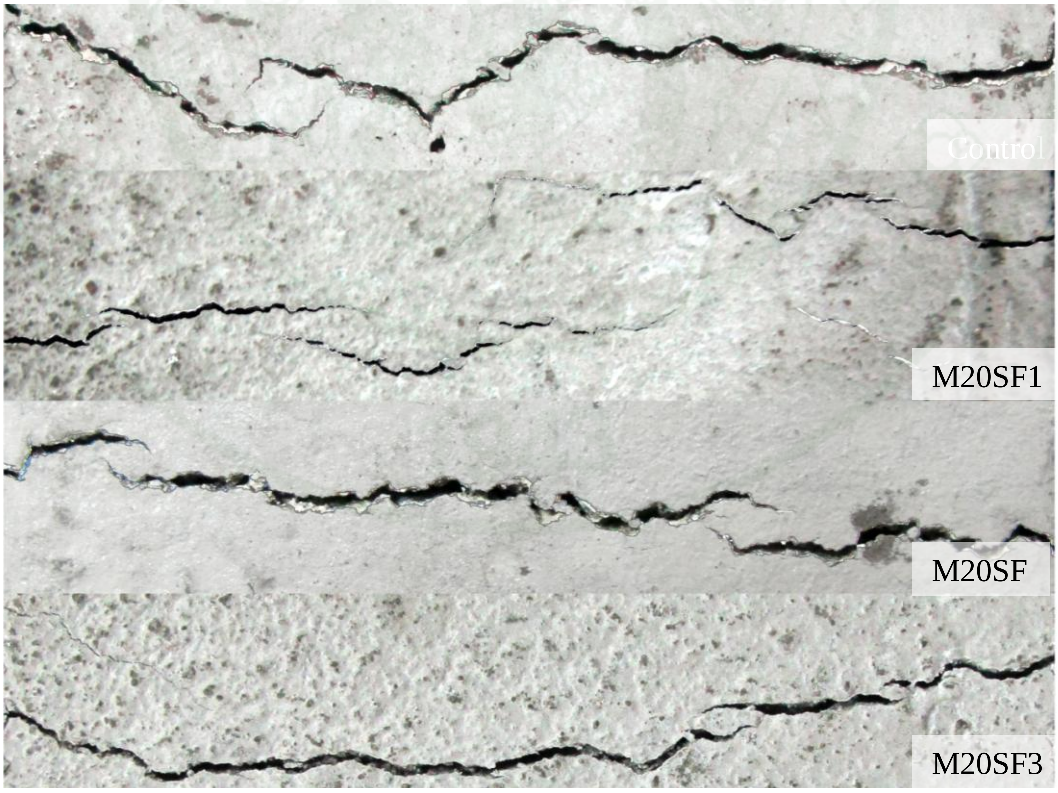

**Appendix Figure 5** Cracked specimens, Series M20 - PVA fiber concrete




**Appendix Figure 6** Cracked specimens, M30- PVA fiber concrete



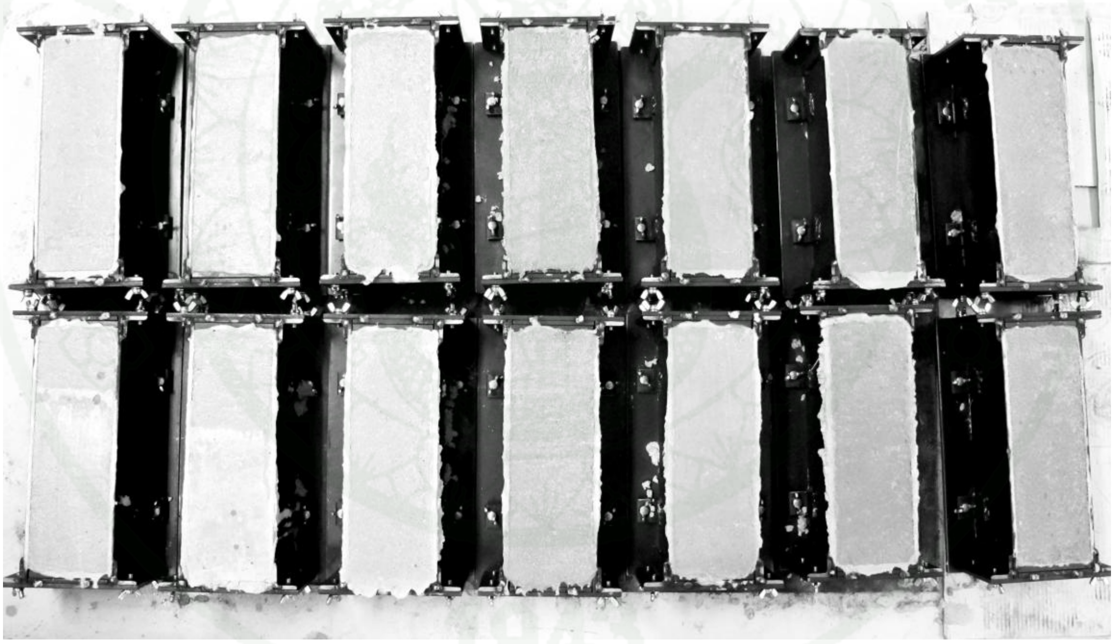

**Appendix Figure 7** Cracked specimens, M20- Steel fiber concrete




**Appendix Figure 8** Cracked specimens, M30- Steel fiber concrete

(a) (b) (c)

**Appendix Figure 9** Split tensile test specimens, a) No fiber. b) Steel fiber and c) PVA fiber



**Appendix Figure 10** Free shrinkage specimens

**Appendix Figure 11** Free shrinkage specimens after unmolding

# CIRRICULUM VITAE

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