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Development of High Strength Self Compacting Mortar with Hybrid Blend of Polypropylene and Steel Fibers

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ABSTRACT

Use of self-compacting concrete (SCC) is gaining popularity due to its flowability and hence higher workability but producing SCC of elevated mechanical properties and better durability aspects often is a challenge to the construction industry. Hybrid fiber systems have been found to be effective in previous research works to improve mechanical properties and thus the issue has been addressed here through research on combination of steel and polypropylene (PP) fibers in SCC mix. Combination of steel and PP fibres has been tried and they seem to affect strength and other properties in different ways. Total Fiber content was kept constant at 1.5%. There was an increase in compressive strength and a much higher improvement in flexural strength through use of hybrid fibers along with durability aspects such as drying shrinkage, water penetration length and loss in strength due to exposure of sea water (90 days) saw considerable improvement. Workability was reduced when fiber was added to flowable SCC used and demanded increase in superplasticizer dosage to attain the same slump value as control.

Keywords: *self-compacting concrete, hybrid fiber, steel fibers, PP fibers, durability*

1. INTRODUCTION

High strength self compacting concrete or mortar is a very popular material because of the almost elimination of vibration owing to ease of flow which indirectly saves time and effort. However, this kind of concrete subjected to axial load shows brittle failure although the load magnitude is high. This is not a very desirable property for structure subjected to heavy loading. Fiber addition to plain matrix has very little effect on precracking behavior but considerably improves its toughness and ductility through crack bridging and delaying the onset of extension of cracks [1].

Previous studies as conducted by Shah and Naaman [2] focused on flexural, compressive strength tests on steel fiber reinforced mortar which revealed that the flexural strength displayed two to three times improvement compared to normal mortar. Acknowledging the fact, however, there are some concerns involved with high dosage of steel fibers such as degraded workability and higher cost. Also, high quantity of steel fiber tend create void and honeycomb owing to high stiffness. Therefore, to address this, the research conducted here was aimed at using two types of fiber to create a hybrid fiber system that might improve the workability and hence yield optimum performance [3].

Corrosion of steel fibers in aggressive environment is another important issue which is argued to be detrimental to bonding of fiber to the matrix. However, Sustersic et al. [4] investigated that only surface corrosion of steel fibers would not harm the bonding under site condition but would help in creating weak zone which crack easily making way for foreign substance to go in and deteriorate the matrix. This hints at the requirement of considerable care and caution using concrete with only steel fiber in cases of combined loading and aggressive media.

Therefore the objective of the paper is to study the development of high strength self compacting mortar with steel fiber only and steel and PP fiber and investigate the strength development and behavior when exposed to sea water along with shrinkage. Exposure to sea water is to test the durability while shrinkage would give an idea of the long term properties of the developed concrete. The durability of concrete is one of its most important properties and dictates the suitability of the use of the material for a particular environment. In most of the cases of aggressive environment, the distress in structures is caused by low durability features rather than strength. Dry shrinkage, one of the main causes of shrinkage cracks that directly impacts the strength and durability of concrete structure tends to happen in hot/ warm and dry climate which aids in loss of moisture from the concrete system. The consequence is length change of concrete member and formation of shrinkage cracks in hardened concrete. Drying shrinkage is irreversible i.e. the original length cannot be regained through wetting.

2. MATERIALS USED AND PREPARATION

2.1. Cement And Sand

In this study, the cement used was ordinary Portland cement (OPC) of grade 52.5 N with the following properties as shown in Table 1. 5% silica fume (SF) was added because of its ability of improving the durability, reducing cost and improving the fresh concrete properties. However, many studies indicate that SF can cause more brittleness and thus ductility is an issue. Therefore, this research also tested the compatibility of SF with hybrid fibres and looked into the properties of concrete in terms of durability and strength. The sand used was locally available. The grading chart is shown in Fig.1. Fineness modulus is defines as the empirical figure calculated by adding the total percentage of fine/coarse aggregates on each sieve and dividing the sum by

100. Low fineness modulus indicates finer aggregate although same value of fineness modulus may be obtained from different particle size distributions. Fineness modulus for the sand used ranged from 2.00 to 3.00. The designed mix proportion was same for all specimens and was kept as cement: sand = 1:1.25 with W/C ratio of 0.32. A high range polycarboxylate based water reducing admixture was used to compensate for the low water-cement ratio and adjust the workability.

Table 1: Specification of OPC used

Properties of OPC used	
Grade	52.5 N CEM I
Initial Setting time (mins)	120
Final Setting time (mins)	220
Fineness (m^2/kg)	350
Density (g/cc)	3.2
Alkalinity	0.5

Table 2: Specification of SF used

Properties of SF used	
Specific Gravity	2.2
SiO_2 (%)	95
Fineness (m^2/kg)	25,000
Bulk Density (kg/cu. m)	1450

2.2. Steel and PP fibres

Researches over centuries have found out that short fibres are effective in reinforcing brittle materials like cement or concrete. Presently, there are numerous types of fibres available in the market for use in concrete or commercial use like steel fibres, glass fibres, synthetic fibres such as PP and PVA fibres etc. With comparatively lower modulus of elasticity, high durability, PP fibres is frequently used with cement or in concrete to enhance the ductility and anti-cracking performance of concrete. PP fibres are also inexpensive, another reason which makes it preferable for commercial use. PP fibres have been found to mitigate plastic shrinkage and early drying shrinkage because of its capability of increasing the tensile property of concrete and bridging cracks [5]. Therefore, PP fibres have been used in the study to minimize brittleness and look into its performance in enhancing durability and other properties.

On the other hand, steel fibres are known for their toughness and crack bridging property. Steel fibres are made from hard drawn steel wire to ensure high tensile property and close tolerances. The main purpose of adding such fibres is to impart ductility while achieving higher tensile strength. Table 3 presents the properties of fibres used in this study.

Table 3: Properties of Steel and PP fibres

S/L No.	Properties	PP fibre	Steel fibre
1	Length (l) , mm	30	20
2	Diameter (d) , mm	0.5	0.10
3	Aspect ratio (l/d)	60	200
4	Specific gravity	7.9	1.4
5	Tensile strength, MPa	1010	900
6	Elastic modulus, GPa	200	20

2.2. Preparation

Silica fume (SF) was added replacing same quantity of cement (5%) and PP and steel fibres were mixed with the unchanged dosage of cementitous materials. When fibres and mineral admixtures are used the materials need to be well dispersed in the mix. In order to distribute and disperse silica fume, steel and PP fibres, Hobert mixer was used. Both the fibres were dispersed into the mixture by hand to achieve uniform distribution. The mixing sequence followed as – the sand (fine aggregate) was added and mixed for first 1 minute, followed by the addition of cement, SF and fibre. This was mixed for another 1 minute. Lastly, the water and superplasticizer were added and mixed for 4 minutes. The dispersion of fibre and SF has great effect on workability and strength of the concrete because if they are not well dispersed, there would be lump formation. Flow value and broken section of the specimen obtained in course of the experiment testified well dispersion of all the components. A flow chart is shown in Fig. 1 to explain the mixing process.

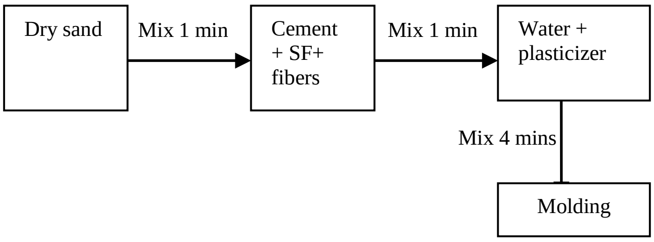

Fig. 1: Flowchart showing mixing procedure

Table 4: Mix designs for trial mixes tested

Mix No.	**1**	**2**	**3**	**4 (Control)**
Cement (kg/m^3)	522.5	522.5	522.5	522.5
Silica Fume (kg/m^3)	27.5	27.5	27.5	27.5
Sand(kg/m^3)	687.5	687.5	687.5	687.5
Steel Fibre (%)	0.9	0.75	0.6	0
PP fibre (%)	0.6	0.75	0.9	0
Water (kg/m^3)	176	176	176	176
Plasticizer (%)	2.2	1.95	1.85	1.65

3. EXPERIMENTAL PROGRAM

3.1. Workability Test

Workability of fresh self compacting mortar can be evaluated by means of flow test and obtaining the flow values. The flow is expressed as the spreading diameter of the fresh concrete composite in the flow test. This parameter can reflect the fluidity of the fresh composite and its cohesive properties. From the spreading under its own weight, segregation resistance of the mortar can be assessed too. The test set up consisted of a flow mould conforming to ASTM C 1437 specification and a flat clean and dry surface big enough to accommodate the flowable mortar. Concrete was poured into the mould which compacted well and do not need any tamping. After the mould was filled, the extra mortar on the top was removed and the surface towelled. Any leaking around the base was checked before the mould was lifted and the mortar was allowed to flow. Reading across was four directions as marked on the surface was taken with callipers and the flow value was expressed as the average of the four readings. Higher flow values indicate highly workable mortar but too high value might not be acceptable as it would indicate higher than required plasticizer dosage or bleeding which might affect strength development and performance.

3.2. Strength test – Compressive and Flexural

Mixtures were cast into 50x50x50 mm cube moulds for compression test and 50x50x250 mm prism for flexural testing. After being cast, samples were covered and transferred to a curing room where temperature was maintained at 22±2 degrees and RH> 95%. After 24 hours specimens were demolded and put in water tank for curing. It is normally accepted that higher load rates will result in higher compression strength and modulus of elasticity results. For this reason, using the ASTM C39 load rate of 0.24 ±0.10 MPa/s (35 ±15 psi/s) is recommended for any standardized compression testing of concrete. However, in case of high strength mortar testing at this load rate would take more than 8-10 minutes to crush the specimen. This objectionably long time led us to alter the loading rate. So, an altered loading rate of 1MPa/ s was used which could complete the testing in 2-3 minutes depending on the strength. For flexural strength, Universal testing machine (UTM) was used with loading rate set at 0.5 mm/min and three point bending method adopted with distance between end supports 100 mm

3.3. Drying Shrinkage Test

Drying shrinkage is defined as the contracting of a hardened concrete mixture due to the loss of capillary water. Drying shrinkage is measured as the strain or length change that the concrete undergoes without any externally applied force. Measurement of length change allows assessing the potential for volumetric shrinkage (expansion or contraction) of concrete over period of time. It is a long term property of hardened concrete. For shrinkage test 3 prism specimens for each mix were prepared , size conforming to ASTM C157/157M (kept at 100 mm square cross section and 285 mm long). The specimens are demolded after 24 hours and kept in the curing room at temperature 20±2 degrees and RH > 95%. After 7 days of curing first shrinkage reading was taken (considered base reading) and immediately after that the specimens were transferred to lime saturated water tank to be cured for 28 days. After 28 days of curing, readings for 10 periods at 7 day interval (i.e. up to 70 days were taken with the help of comparator fitted with dial indicator.

3.4. Water Penetration Test

Water penetration is evaluated by the measurement of the depth up to which water can travel under pressure.100 mm cube specimen were used for water penetration test and procedure conforming to BS EN 12390-8 was followed. After demoulding, surface of the specimen to be exposed to water was roughened before it was put in the water tank to be cured for 28 days. Water pressure of 500 KPa was applied to the 28 day old specimens for 72±2 hours. Periodical observations were made on the surface of the specimens to note any presence of water. The test set up is shown in Fig. 2. After application of pressure for specified time, the specimen on removal from the apparatus was wiped to remove any excess water. The specimens were broken in two halves perpendicular to the face of the application of pressure. As soon as the water profile becomes visible upon little drying, the depth of penetration in each half was measured and the maximum reading was taken. There were 3 samples cast for each mix and thus the penetration for each was calculated by averaging the maximum penetration in case of each.

3.4. Test for strength loss due to exposure to sea water

One of the major durability issues in case of concrete structures arise from exposure to sea water. Concrete incorporating steel fibres is subjected to risk of fibre rusting and reduction of bonding or crack formation due to prolonged exposure to sea water. Structures subjected to wetting and drying in marine environment are more vulnerable compared to completely submerged structures. The experiment conducted here was designed to study the effect of wetting and drying on strength (compressive and flexural) fibre reinforced specimens. Therefore the specimens were subjected to two cycles (12 hrs each) of wetting and drying each day. This was made possible by submerging the specimens in sea water for 12 hours and then taking it out of water and leaving it in open air to dry for next 12 hours. Compressive and flexural strength tests were performed at 28, 56 and 90 day.

Fig. 2: Water penetration test set up

4. EXPERIMENTAL RESULTS AND ANALYSIS

4.1. Effect on workability

Fig. 3 illustrates the variation of flow of the concrete composite with hybrid fibre system. As shown in Table 4 , four different mixes were prepared including control mix without any fibre and tested for flowability. It is observed from the graph that the flow values show a decreasing trend from mix 1 to mix 3. Although the total fibre volume was kept constant, slump decreased with increase of PP fibre content. There was a sharp decrease of 12% in flow from control for the mix 1 and 14 % and 15% when the PP fibre percentage was raised in case of mix 2 and mix 3.

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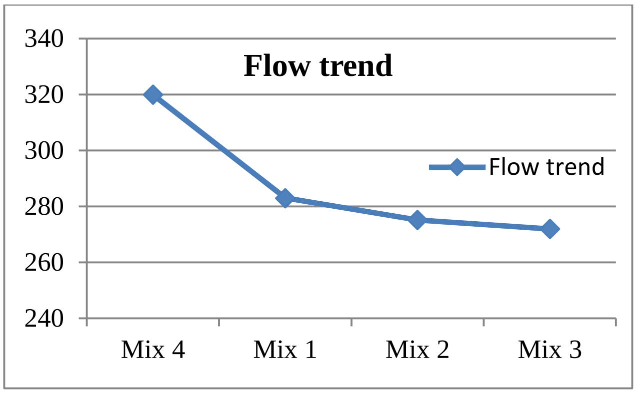

Fig 3: Effect of hybrid fibre system fibre addition on workability

Addition of fibres decrease the workability [6] but the results here show that flow is more affected or decreased especially by PP fibres more than steel fibres which has also been found out in existing research [7]. Increase of fibre volume fraction actually means larger number of fibres in unit concrete mixture and thus more absorption of water on the fibre surface. Therefore, the obstructive effect of fibre turns out to be more prominent when PP fibres are used. Addition of PP fibres has comparatively more adverse effect on mixtures containing silica fume as silica fume is much (around100) times finer with higher specific surface area than cement and tends to form a sticky mix thus requiring higher superplasticizer dosage to be added to the mixture.

4.2. Effect on Strength

4.2.1 Effect on compressive strength

The results of the compressive strength test shows that compressive strength increase with the addition of hybrid fibres although the maximum percentage increase in strength is up to a modest 2.50% above control This slight increase is perhaps attributable to the toughness increased and better mechanical bond between fibres and the matrix. Also under crushing force when microcracks are generated fibres offer resistance to opening up of cracks and delay the propagation of cracks ([9], [10]). Mix 1 shows highest increase in compressive strength owing to the comparatively less volume fraction of PP fibres and relatively higher fraction of steel fibres. Hybrid fibres offer different restraints [11] and in this case steel fibres are more effective than synthetic fibres.

4.2.2 Effect on flexural strength

Flexural strength showed considerable increase with addition of hybrid fibres. The experimental results registered a maximum increase of about 20.50% compared to control mix at 28 day. Mix 1 showed highest improvement in strength which can be explained through bond strength and energy for fibre pull out. Under flexure, there is a certain level of fracture energy required to generate cracks that result in specimen failure. Fibres offer resistance to the generation of cracks and crack opening. The fracture energy absorbed for fibre pull out is related to bind strength and fibre length. Higher bond strength offers higher stress capability at relatively large crack opening [12]. Flexural strength is a function of combined bond strength of all the fibres in the critical fracture zone. Although PP fibres also contribute to resistance but steel fibres are more effective due to their toughness and longer dimensions in this case. The pull out energy required is more resulting in higher bridging stress and improved flexural strength for Mix 1.

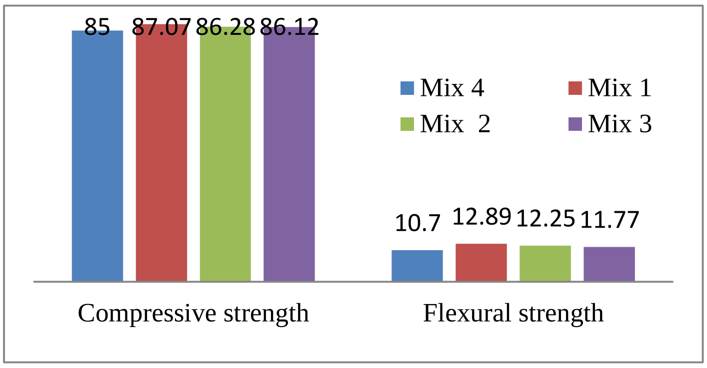

Fig 4: Effect of hybridization on flexural and compressive strength

4.3. Effect on Drying Shrinkage

Drying shrinkage test on the sample mixes indicate that drying shrinkage strain decrease with incorporation of hybrid fibre system. As can be seen from Fig. 5, fibres have restricted shrinkage effectively reducing shrinkage strain considerably compared to control mix 4. Short PP fibres have been effective in reducing shrinkage which is ascertained from the fact that mix 1 shows lowest strain among three sample mixes. This is in line with the research previously conducted by Malhotra et al [13] and Liu et al. [14] which confirms that PP fibre mixed into cement mortar decreased its drying shrinkage. Hybrid fibre mixed cement mortar display low shrinkage because of effective restraint in movement of moisture made possible by fibres through bridging and stitching cracks. A combination of steel and short PP fibres would expectedly show low shrinkage because of the combined effect- steel fibres would bridge cracks while short PP fibres would be effective in blocking the pores and reducing moisture movement. When the matrix experiences tensile stresses induced by drying shrinkage, fibres can restrain the shrinkage by shear along fibre matrix interface [15].

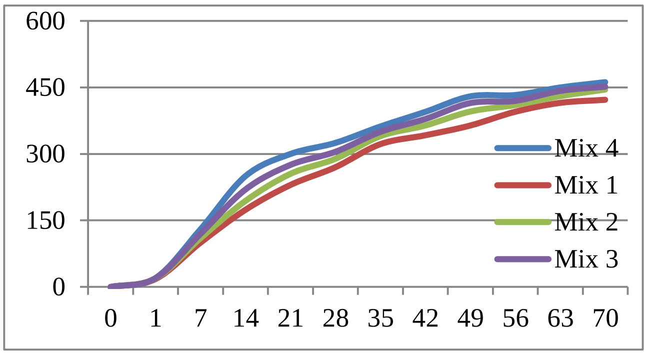

Fig. 5: Effect of hybrid fibres on drying shrinkage

4.4 Effect on Depth of Water Penetration

The effect of hybrid fibre system in concrete mix on the depth of water penetration has been illustrated in Fig. 4. As can be seen in the relation graph use of hybrid fibres had significant effect on water penetration depth of the self compacting mortar. Use of silica fume in the flowable mix already aided in formation of dense microstructure because of finer particles, besides use of fibres improved its resistance to penetration and reduced the depth of penetration into the concrete under pressure. Although the total percentage of fibres used was same in all the mixes, the graph suggests that depth of penetration reduced with increase of PP fibre volume. A decrease in depth of penetration of about 7.2% has been observed for mix 1 and 10% and 11.5% for mix 2 and mix 3 respectively from the control mix (mix 4) indicating a downward trend with more amount of PP fibres. Hybrid fibre system creates a very dense network if distributed uniformly within the mix forming a grid structure that not only aids in lower water permeability or penetration depth but also reduce bleeding [8]. This grid network also breaks the continuity of pores and interconnectivity of porous channels making the mortar more impermeable. Moreover, combination of steel fibres and PP fibres impart cracking resistance reducing microcracks in the matrix which otherwise develop due to early age shrinkage and may act as seepage channels. Thus based on experimental observations it can be concluded that hybrid fibres in mix actually improves water permeability with especially higher percentage of PP fibres thus imparting better durability feature.

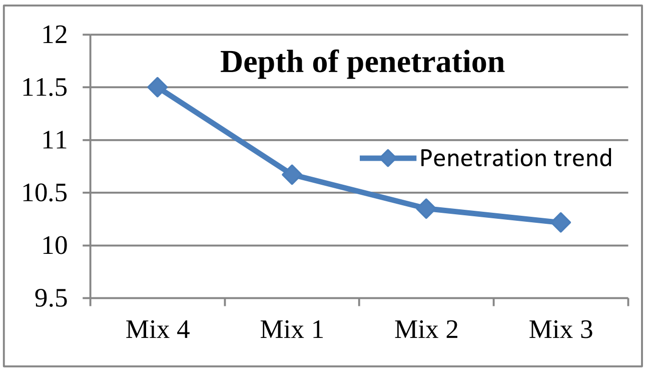

Fig 6: Effect of hybrid fibre system on water penetration

4.5. Effect on strength upon exposure to sea water

The strength results hybrid fibre mixes exposed to sea water at 28, 56 and 90 days are presented in Fig 6. The lowest reduction in compressive strength and flexural strength of hybrid fibre mix at 90 d showed a reduction between 8 to 12% and 5%-9% respectively. The minimum reduction in compressive strength may be due to the ability of combination of PP fibres and steel fibres to make the mixes more impermeable.

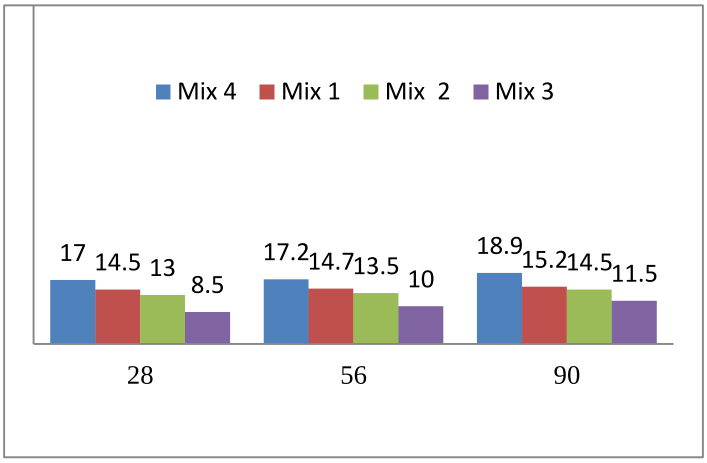

Fig. 5: Effect on compressive strength upon exposure to sea water

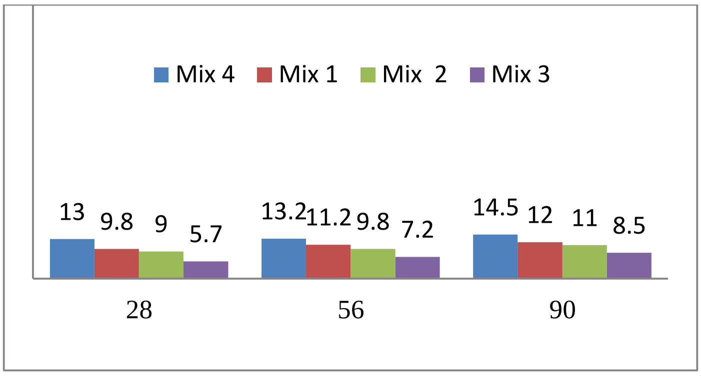

Fig 6: Effect on compressive strength upon exposure to sea water

Highest reduction in flexural strength was obtained in the mix with higher volume fraction of steel fibres i.e. mix 1. This finding is coherent with previous researches [16] that surface deterioration of steel fibres become worse under flexure and thus register highest reduction in strength where the volume fraction is larger. Thus, hybridization of steel and PP fibres improves durability performance of concrete mix.

5. CONCLUSION

This paper focused on experimental studies on performance and durability features of self compacting concrete with hybrid fibre systems. Based on the experimental results, the following conclusions can be reached at.

a) Hybrid fibres have adverse effect on flow of concrete and it workability. Fibres obstruct flow thereby reducing the flow value and synthetic fibres like PP fibres have the tendency to form lumps and make the mix less workable. Higher dosage of admixture is needed to achieve the same workability as control mix.

b) Combination of fibers has excellent effect on strength. As is revealed from the experimental result, flexural strength showed about 20.50% increment for mix 1 (highest) although there was modest increase in compressive strength (about 2.50% maximum) . Mix 1 which contained highest amount of steel fibres showed highest improvement supporting the fact of effective crack bridging property of steel fibres.

c) Drying shrinkage was significantly reduced by hybridization of fibers. Mix 1 showed lowest shrinkage strain (about 17% below control) followed by mix 2 and mix 3. Although the difference in shrinkage strain were not very significant, the data shows that in long term steel fibres is the one majorly contributing in resisting shrinkage strains and shrinkage cracks more than PP fibres.

d) Water penetration depth reduces considerably from control with the addition of hybrid fibres. More volume fraction of PP fibres meant highest reduction in depth of water penetration.

e) Mix with hybrid fibre system displayed lower reduction in strength when exposed to sea water and subsequently the process of wetting and drying. Lowest reduction obtained was approximately 7 % which is considerable compared to the reduction in case of control mix.

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