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Research Article

Prediction of strength and shrinkage of ternary blended concrete with fly ash, slag and silica fume

T. Sakthivel[1]*, K. Arulraj[2],

[1] Department of Civil Engineering, PSG Institute of Technology and Applied Research, Coimbatore, Tamil Nadu (India), Email: thanga.sakthivel@gmail.com

[2] Department of Civil Engineering, Dr. Mahalingam College of Engineering and Technology, Coimbatore, Tamil Nadu (India), Email: arulraj191295@gmail.com

*Correspondence: thanga.sakthivel@gmail.com

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Abstract: In the recent years, there has been increased in concern on shrinkage response of concrete systems as abundant cases of premature deterioration were reported. The major factors affecting the deterioration of a concrete system are quality, composition and the surrounding environment. In connection with this, the work concentrates on the study of long-term effects on materials used in the concrete (supplementary cementitious materials SCMs) such as fly ash, slag and silica fume as a blended concrete system. To carry out the experimental work, nine concrete mixes were designed for varying proportions of SCMs and w/b. Evolution of compressive strength, elastic modulus, shrinkage and selected durability parameters were tested under a controlled laboratory condition. Based on the work, it was found that the inclusion of fly ash, slag and silica fume on the concrete systems enhance the compressive strength in long-term, also the shrinkage response of the ternary systems shows a substantial reduction in the measured strain. Durability performance like chloride penetration and sorptivity had a better performance in comparison with the conventional concrete systems.

Keywords: Supplementary cementitious materials (SCM), fly ash, silica fume, slag, long term performance, shrinkage, durability.

1. Introduction

Supplementary cementitious materials (SCMs) such as fly ash, slag and silica fume are being used for major construction works. These SCMs are used for manufacturing high performance concrete resulting in dense durable concrete members (Kar et.al, 2012). The synergetic action of SCMs in concrete possibly could enhance the microstructure and its long-term mechanical and durable performances. Also, the substitution of OPC with SCMs could lead to a better sustainable concrete construction practice (Chore and Joshi 2015, Juengera and Siddique 2015) Substitution of slag and fly ash in the OPC concrete systems as a ternary blend lowers the early age properties, however, prolonged curing resulted in similar strength of conventional concrete system (Li and Zhao 2003, Praveen Kumar and Ravi Prasad 2019, Sadrmomtazi et al., 2017, Akyuncu et al., 2019, Sakthivel et. al., 2019).

Factors affecting the shrinkage response of concrete are usually interrelated, however, they were grouped into (i) material properties and (ii) ambient conditions (temperature and humidity). The material properties such as water-binder ratio, total binder content, physical properties and chemical composition of binder, air content, chemical and mineral additives could alter the shrinkage response at different rate (Mehta and Monteiro 2006, Neville 2006) Incorporation of slag tends to have a marginal effect on shrinkage of concrete. Correspondingly, Class F fly ash reduces drying shrinkage with increase in the dosage in comparison with the non-blended concrete systems (Gesoğlu and Güneyisi 2009). High dosage of silica fume resulted in increase in the shrinkage in short-term, nevertheless, Class F and Class C fly ash in combination with silica fume or slag diminish the adverse consequence of slag or silica fume (Güneyisi 2010). In the case of durability performance, the resistance to chloride penetration and the permeability of blended concrete improves substantially without losing strength by a fractional replacement of cement with SCMs because of high cementitious effect in the conventional concrete and high content of the pozzolans in the whole system (Sadrmomtazi et al., 2017, Sumrerng and Prinya 2014). The use of appropriate content components in ternary blends will allow binders to fulfil the specified mechanical requirements. Besides, certain influence of the effect on durability performance is detected (Alonso 2012). In the recent past, there is a need of developing a long-term durable concrete member which is to be environment friendly and thus sustainable (Richardson 2002).

Long-term Testing of a blended cement concrete requires a high laboratory work and also, the design engineers have to wait for the data needed that has to be incorporated. In such conditions predictions of data can be obtained with available input parameters. In connection with this, present work focused on the ternary blend systems on the long-term performance (say, strength and shrinkage) and limited durability parameters on contact with chlorides and water. The investigation was restricted on the addition of fly ash, slag and silica fume on the primary binder (say, OPC) and the test was performed under a controlled laboratory condition.

2. Materials and methods

Ordinary portland cement of 53 grade, Class F fly ash, slag and silica fume were used to produce ternary blends in concrete. The oxide composition was tested in accordance with IS:1727 2004, ASTM C204 2011 and physical properties of materials used were presented in Table. 1. Based on the result, the values obtained are within expected range. River sand and crushed granite was used as fine and coarse aggregate respectively in a proportionate of 40:60. SNF based superplasticizer was used to get a desired slump of 100±10 mm. The concrete mix was design in accordance with IS 10262, 2010 and the mixtures were prepared in a motorized mixture machine.

Table. 1 Chemical composition and physical properties of the binders.

Binder	CaO	Al_2O_3	Fe_2O_3	K_2O	MgO	Na_2O	SiO_2	Specific gravity	surface area (m^2/kg)
OPC	65.11	4.07	4.36	0.25	0.92	0.22	21.42	3.16	330
Class F fly ash	1.25	28.02	4.02	1.53	0.59	0.20	60.12	2.50	380
Slag	34.55	18.38	1.65	0.67	8.98	0.45	33.02	2.88	350
Silica Fume	0.001	0.043	0.04	-	-	0.003	99.886	2.20	Data not available

The concrete mixtures were prepared for water to binder ratio of 0.40, 0.45 and 0.50 with a total binder content of 310 kg/m^3. A total of nine mixes were prepared with two different replacement levels of cement with three SCMs. Mixes TER-1, TER-3 and TER-M5 are designed with 20% of Class F fly ash and slag to total binder, similarly, TER-2, TER-4 and TER-M6 were prepared with 15% of silica fume and slag to total binder content. Table. 2 provides the mix details of the concrete.

Table. 2 Concrete mixture details.

Sl. No	Designation	W/b	Total binder	OPC	Class F fly ash	Slag	Silica fume	Fine aggregate	Coarse aggregate
			(kg/m^3)						
1	OPC-M1	0.40	310	310	0	0	0	767	1363
2	TER-M1	0.40	310	186	62	62	0	757	1345
3	TER-M2	0.40	310	217	0	47	47	759	1350
4	OPC-M2	0.45	310	310	0	0	0	773	1315
5	TER-M3	0.45	310	186	62	62	0	762	1297
6	TER-M4	0.45	310	217	0	47	47	765	1302
7	OPC-M3	0.50	310	310	0	0	0	777	1268
8	TER-M5	0.50	310	186	62	62	0	766	1251
9	TER-M6	0.50	310	217	0	47	47	769	1255

Cube compressive strength test was performed on 150 mm cube specimens at the age of 7, 28, 90 and 180 days with a loading rate of 140 kg/cm^2/min (IS 516, 2004). The static elastic modulus of concrete was tested on 150 mm diameter and 300 mm height as recommended by ASTM C469, 2010 at 28 days. In accordance with ASTM C157, 2008, drying shrinkage response of concrete was performed in 75 × 75 × 285 mm prismatic specimens after 28 days of curing (t_0= 28) and monitored the change in the length until 200 days.

The length comparator frame of 320 mm in height with a digital dial gauge of 0.001 mm precision was used to determine the change in length of the specimens. Before each reading, the reference bar was placed in position in the comparator and zero value of the dial gauge was set. After that, the specimen was placed on the length comparator and the dial gauge reading was observed to calculate the strain measurement. Rapid chloride permeability tests were performed as shown in Figure 1 in accordance with ASTM C1202, 2012 recommendation on the cylindrical sliced specimen of 100 mm diameter and 50 mm thickness. After the desired curing period, specimens were kept in the vacuum desiccator for about 24 hours before proceeding the test. A potential of 60 Volts was applied on the vacuum saturated specimen. One side of the specimen was exposed to 0.3 M of NaOH solution and the other side being exposed to 3% of NaCl solution.

The resulting current was measured at a time internal of 30 minutes and continued for about 6 hours. From the measurement, the total charge passed in Coulombs was calculated. Different classes of concrete were categorized based on the total charge passed. The sorptivity test was carried out as per the recommendation of ASTM C1585, 2012. Concrete specimens of 70 mm diameter and 30 mm thickness was used. The specimens were oven dried at 50°C for 7 days. Curved surface of the concrete specimens was sealed with two compound epoxy and cooled in the desiccator for 3 hours. Knife edge supports were placed in a tray and the saturated calcium hydroxide were poured in to the tray. After measuring the initial weight, the specimens were placed on the knife edge in such way that the solution level is around 2 mm above the base of the specimen. To get the sorption of the specimens, the mass of the specimen was taken at 5,10, 15, 20, 25 and 30 minutes' interval of time.

Figure 1. Test setup of rapid chloride permeability of concrete.

3. Result and discussion

3.1. Compressive strength and elastic modulus

From Figure 2 the ternary blended concrete systems display a significant increase in the compressive strength in comparison with the conventional concrete. TER-M2 shows the highest compressive strength in comparison with the other mixes. The trend observed on this mix was that the rate of gain in strength of about 1.75 times of concrete with SF content was seen to be very high on initial period and it stable after 90 days. However, in case of fly ash blended systems, it seems to have attained lower initial strength say, at 7 days and it continuous to gain strength substantially till 90 days.

This could be that fly ash initiate the pozzolanic reaction after 7 days and substantial strength gain due to pozzolanic reaction would result after 28 days. Also, from Figure 2 it is clear that the compressive strength of the conventional concrete systems is low compared with the ternary blended systems of the same group. In the case of the ternary mix with fly ash and slag doesn't seems to yield higher strength in comparison with silica fume and slag, it continues to gain strength considerably even after 90 days but, the strength development of silica fume concrete was seen considerable up to 90 days.

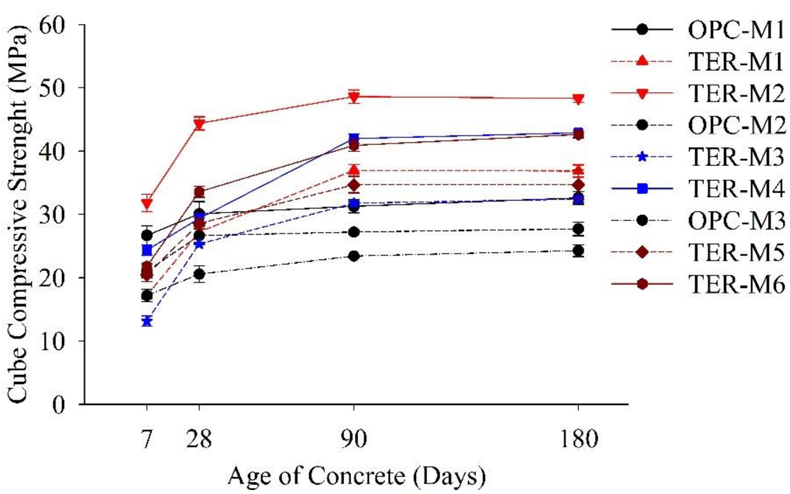

Figure 2. Compressive strength development of ternary blended concretes.

A comparison with the laboratory cube compression was carried out with the ACI 2092R,2008 prediction formulae to find the applicability of the model equation for blended cement concrete systems. The empirical equation is expressed as: $f_c'(\mathrm{t}) =$

$\frac{t}{\alpha+\beta\ t}\ f_c'(28)$ where, α and β are constants, $f_c'(28)$ is the mean cylinder compressive strength of concrete at 28 days and $f_c'(t)$ is the compressive strength of concrete at any age *t*. As seen from Figure 3 it shows that there is a good correlation between the experimental and prediction values (calculated with the reference of the standard concrete specimens), since all the data set has been falls within the 95% of the prediction interval.

As seen from Figure 4, the elastic modulus of conventional concretes is comparatively low than its equivalent ternary blended concrete systems. As like in the cube compressive strength, the elastic modulus of TER-M2 is the highest recorded in all other mixes. The elastic modulus value obtained by all other mixes were relatively in the same order of cube compressive strength. This seems to be satisfying the concept of higher the cube compressive strength is the higher the elastic modulus. Altogether, in the assessment with the ternary blended systems, OPC mixes lead to the least yield both in compression and elastic modulus, which directly indicates that the ternary blended systems enhance the mechanical performance of the concrete in a long term.

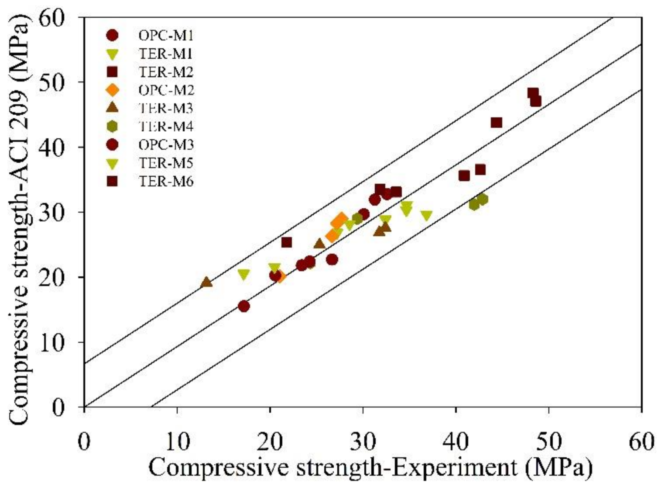

Figure 3. Comparison of compressive strength with ACI 209 model prediction.

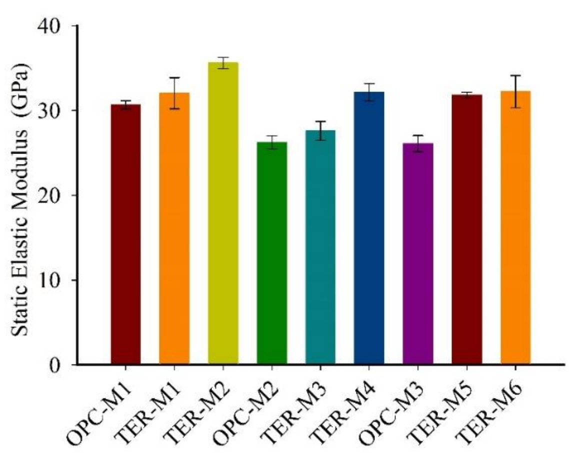

Figure 4. Static elastic modulus of ternary blended concretes.

3.2. Shrinkage response

From Figure 5 it is clearly seen that the conventional concrete mixes show an increase in the drying shrinkage at any exposure time. Also, the ternary blended systems resulted in comparatively lower shrinkage strain than all other conventional mix. Mixes TER-M2, TER-M4 and TEM-M6 show the drying shrinkage of 212, 243 and 253 microstrains at the end of 200th

day and TER-M1, TER-M3 and TER-M5 shown the shrinkage of 266, 277 and 290 microstrains. However, the OPC-M1, OPC-M2 and OPC-M3 resulted in 311, 350 and 342 microstrains. Also, the rate of increase in shrinkage strain after 150 days of exposure in ternary blends is observed to be reduced than conventional systems. Thus, ternary blended systems decrease drying shrinkage than conventional concrete in long-term, this could be because of pore refinement in the SCM blended concrete systems.

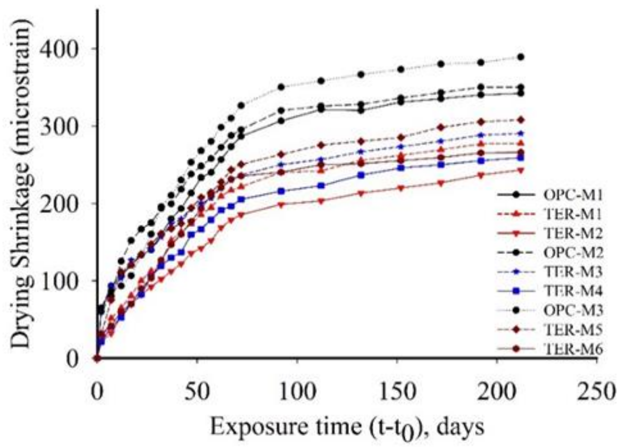

Figure 5. Shrinkage evolution of ternary blended concrete systems

To estimate the shrinkage strain in the absence of the data, a comparison between the laboratory test with the strength-based shrinkage prediction models such as B4s (Bažant 2015) and CEB fib 2010. A detailed explanation of the model parameters, procedure adopted has been adopted from Sakthivel., et.al., 2021 and the error between the laboratory data and the model was calculated as,

$$Error = (predicted \sim measured)\ in\ microstrian \qquad \text{Eq (1)}$$

A positive error in the Equation 1 specifies that the model overestimates the test data and a negative error indicate that the model underestimates. Table. 3 shows the error difference between the measured and predicted shrinkage strain. Based on the comparison, it can be concluded that, the B4s model has a minimal error difference compared to the fib MC2010.

Table. 3 Comparison of experimental and predicted shrinkage strain and the error at 200 days.

Sl. No	Designation	Experimental (microstrain)	Predicted shrinkage (microstrain)		Error (microstrain)	
			B4s	fib MC 2010	B4s	*fib* MC 2010
1	OPC-M1	340	400	530	60	190
2	TER-M1	280	320	350	40	70
3	TER-M2	240	300	420	60	180
4	OPC-M2	350	300	430	-50	80
5	TER-M3	290	250	520	-40	230
6	TER-M4	260	350	340	90	80
7	OPC-M3	390	460	300	70	-90
8	TER-M5	300	350	420	50	120
9	TER-M6	270	280	350	10	80

3.3. Chloride migration and sorptivity index

It clearly shows that mixes TER-M2, TER-M4 and TER-M6 shows high resistance to chloride penetration and water sorption. Similarly, TER-M1, TER-M3 and TER-M5 shows better resistance to chloride penetration as-well as sorption in comparison with the OPC mixes and is characterized as low chloride ion permeable concrete mix and good sorptivity indexed mix. All the OPC mixes yield higher chloride penetration number than the ternary blended systems leading to term OPC-M1, OPC-M2 and OPC-M3 are moderate chloride ion permeable mix and it was in the range of 2000 to 3000 coulombs for the water to binder ratios considered. However, in sorptivity index, OPC-M1 and OPC-M2 is characterized as good and OPC-M3 is characterized as poor. Higher resistance to chloride ion permeation and water sorption on TER-M2, TER-M4 and TER-M6 is found to be higher since, the ternary blends with silica fume and slag accelerated the pozzolanic reaction at early age thus by converting maximum cementitious material into calcium silicates and filling up the empty void spaces on which the particle passes the current to another end. Similarly, TER-M2, TER-M4 and TER-M6, pozzolanic reaction was delayed by the presence of fly ash**.**

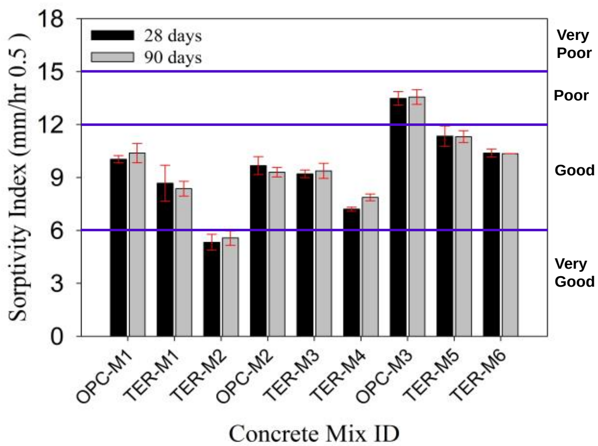

Figure 6. Sorptivity index of the concrete specimens.

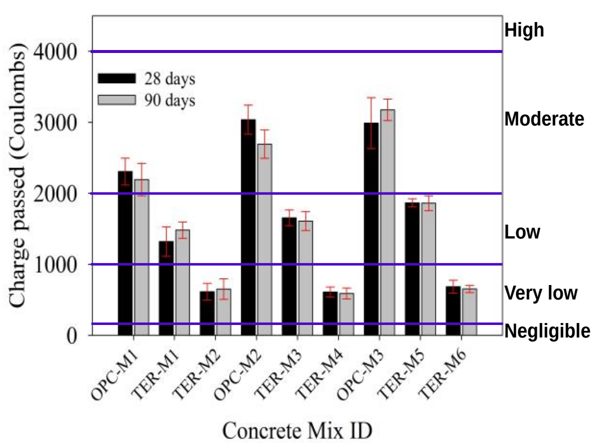

Figure 7. RCPT charged passed on the concrete specimens.

4. Conclusions

Based on the test conducted on the ternary blended concrete mixes, the following conclusion has been drawn

1. Ternary blended concrete shows a better performance than OPC mixes. Also, for a reduction in w/b from 0.50 to 0.40, the concrete displays improved in the long-term strength and durability performance.

2. Incorporation of fly ash, slag and silica fume provides a better performance as a blended concrete in the evolution of compressive strength, the increase in the strength was in the range of 5 to 10 MPa in fly ash and slag concrete and 10 to 15 MPa in the case of slag and silica fume systems in comparison with the non-blended concrete systems. The same was observed in the static elastic modulus of concrete considered in this study.
3. Drying shrinkage response of ternary blended concrete shows a substantial decrease in the strain, in comparison with the non-blended systems. Slag and silica fume concrete showed a lower shrinkage strain of 210 microstrain for a water to cement ratio of 0.40. This could reduce the adverse effect of shrinkage cracking in the concrete. Also, the B4s model reflects the minimal error difference with the laboratory test data. Hence, in the absence of the detailed laboratory test, prediction models can be used to estimate the long-term shrinkage response of blended concretes.
4. Increased resistance to chloride penetration and water absorption on the ternary blended concrete mix was observed. Thus, indicating that the ternary blended concretes are highly durable than the conventional concrete systems.

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