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Strength and durability studies on high strength concrete using ceramic waste powder

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Abstract. This paper summarizes the study on effect of ceramic waste powder as partial substitute to cement in binary blend and along with silica fume in ternary blend high strength concrete in normal and aggressive environments. Strength parameters such as compression & tension and durability indices such as corrosion measurement, deterioration, water absorption and porosity were studied. Ceramic waste powder was used in three different percentages namely 5, 10 and 15 with constant percentage of silica fume (1%) as substitutes to cement in ternary blend high strength concrete was investigated. After a detailed investigation, it was understood that concrete with 15% ceramic waste powder registered maximum performance. Increase of ceramic waste powder offered better resistance to deterioration of concrete.

Keywords: ceramic waste powder; H_2SO_4; NaCl; half cell potential; compressive strength

1. Introduction

Concrete is the highest consumed material after coal, oil and steel among the materials which are used in quantities and become unsustainable in the long term, it requires higher cement content for strength development which results in higher carbon emissions. Portland cement is the major source of carbon emission and the percentage of total carbon emissions associated with Portland cement increases considerably with increase in the higher strength concrete mixes. It is estimated that the carbon emissions due to concrete manufacturing process, range between 0.3 and 0.4 ton of CO_2 per cubic meter of concrete, depending on the type of concrete (Flower and Sanjayan 2007). So it is understood from the above statements that to control the emission of carbon in concrete the use of Portland cement in concrete must be minimized.

To achieve the concrete with controlled carbon emissions and reduced Portland cement content, supplementary cementitious materials received from industries as by-products such as Ground granulated Blast Furnace Slag, fly ash, silica fume can be used partially in concrete. These supplementary cementitious materials termed as pozzolanic (rich in silica content) have little carbon emissions compared to Portland cement and can improve strength much better especially in high-strength concretes and high performance concrete where the usage of cement is almost twice that of the cement used for conventional concrete and water/cement ration is also kept as low. Fly ash is one of the widely used admixtures in concrete, obtained as waste from thermal power plants.

Many previous research works (Jaturapitakkaul *et al*. 2004, Saraswathy *et al*. 2003, Chalee *et al*. 2010) on fly ash showed that concrete incorporated with fly ash has the benefit of reduced heat of hydration. Research works on GGBS (Atis and Bilim 2007, Teng *et al*. 2013, Sharmila and Dhinakaran 2015) and Silica fume (Shanmag 2000, Apparao 2001, Kartikeyan *et al*. 2014) as partial replacement for cement in concrete reveal their suitability to act as a supplementary cementitious material imparting strength and corrosion resisting properties to concrete. But, since dumping of industrial wastes are becoming a major environmental problem in recent days, many works are being tried with construction or industrial wastes as mineral admixtures in concrete either as partial replacement for cement or fine aggregate or coarse aggregate since recycling is the best option for disposal. Such a concrete containing industrial waste as an aggregate is known as green concrete. Senthamarai *et al*. (2011) had developed recycled aggregate concrete using ceramic electrical waste as coarse aggregate in concrete. On performing several experimental investigations on permeation characteristics using the recycled aggregate for six different water cement ratios and comparing the results with that of conventional concrete, the authors found no significant change in the permeation characteristics of the recycled aggregate concrete and the recycled aggregate concrete indeed possessed higher permeation characteristic values than the conventional concrete.

Many researchers focused on use of powder obtained from waste ceramic tiles as replacement to cement and studied characterization, rheological and mechanical properties of concrete. They also studied the pozzolanic activity of the ceramic waste in admixed concrete. They concluded that use of ceramic waste as partial substitute to cement yielded better results in mechanical properties of concrete (Ay and Unal 2000, Lavat *et al*. 2009, Toledo

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Filho *et al*. 2007, Mas Maria *et al*. 2015, Lavat *et al*. 2009, Heidari and Davoud, 2013, Torgal and Jalali, 2010, Medina *et al*. 2013).

Ergun (2011) used diatomite, along with waste marble powder an industrial by product, obtained during the process of sawing, shaping and polishing of marble and which cannot be recycled or used in any, as partial replacement for cement. The results indicated that diatomite and waste marble powder when added individually to cement in 10% and 5% respectively and the ternary blended mix with 5% waste marble powder + 10% diatomite showed best compressive and flexural strength giving an idea that other than the usual pozzolanic materials, industrial waste products can also impart better strength characteristics.

Halicka *et al*. (2013) presented results regarding possible usage of non-biodegradable industrial waste as an aggregate in concrete. Waste ceramic sanitary ware was used as aggregate by the authors. It was reported that, though there was a decrease in strength initially the concrete found to exhibit high compressive and tensile strength and can be recommended for special type of concretes such as abrasion resistance concrete and for structures meant for working in high temperatures.

Pacheco-Torgal and Jalali (2010) tried reusing ceramic wastes in concrete in various forms such as partial replacement for cement, fine aggregate and also for coarse aggregate. Their results indicate that when ceramic powder was used as partial replacement for cement, the strength parameters were not very high but their durability characteristics were better than control concrete. The same trend continued when ceramic wastes were used as partial replacement for fine and coarse aggregate and the authors in their report present that a 20% replacement of cement by ceramic wastes help in increasing the durability properties of concrete in spite of the minor loss occurred in strength.

Vejmelkova *et al*. (2012) presented experimental works regarding the basic physical characteristics, mechanical and fracture-mechanics properties, durability characteristics, hydraulic and thermal properties of high performance concrete with up to 60 % of Portland cement replaced by fine-ground ceramics and identified that better results were obtained with 10% replacement of cement with fine-ground ceramics Heidari *et al*. (2013) performed experimental investigations on compressive strength and water absorption for binary blended concrete with as a partial replacement material and tried also for ternary blended mix with ceramic powder and nano SiO_2. The results of the study indicated that cement replaced with fine ground ceramics by 10% to 25% and 0.5% to 1% of nano- SiO_2 showed improved compressive strength and less water absorption capacity. The authors also mentioned that adding ceramic powder up to 20% did not have any negative effect in compressive strength and increasing the ceramic powder beyond that lead only to reduce the water absorption property of concrete. Sayieda *et al*. (2015) performed tests on geopolymer resin with alkali activated ceramic waste with and without the two calcium sources. They replaced alkali activated waste with 10 to 30% of concrete waste as well as 10 to 30% of GGBFS. They concluded that replacing alkali activated ceramic waste with GGBFS had high reactivity than concrete waste. The above literatures dealt with using any industrial waste that becomes a problem as a mineral admixture in concrete. This paper reports the behavior of high-strength green concrete made with waste ceramic tiles powder as a partial replacement for cement and compares the results with works done using ceramic powder blended with silica fume as mineral admixture. The objective of this work is to elaborate the use of the waste ceramic tiles which would become a problem if not cleared and to suggest a suitable way to dispose the waste tiles as mineral admixtures in concrete, which otherwise would create a problem in dumping.

2. Materials and methods

2.1 Material properties

Ordinary Portland cement of grade 53 was used for this research. Table 1 shows the chemical composition of cement used. Ceramic powder was prepared by grinding waste ceramic tiles in dry ball mill. Waste ceramic tiles are fed into the dry ball mill with 7 steel balls of diameter 30 mm weighing 400 gm each. The ceramic tiles were subjected to grinding for different grinding periods such us 30 minutes, 45 minutes and 60 minutes and then the powder obtained was sieved through a 75 micron sieve to collect particles finer than cement. Fig. 1 shows the ball mill used for grinding and Fig. 2 shows the images of ceramic particles before grinding and after grinding. The samples of ceramic powder ground at different durations were subjected to Particle size analysis and sample which is finer was used for the research work. The chemical composition was found using *X*-Ray Fluorescent (XRF) and it is presented in Table 1. The particle size of the ceramic powder was checked by zeta analyzer to ensure that their size is less than the size of cement. The particle sizes of ceramic powder and silica fume were 2.48 μm and 0.64 μm respectively.

Silica fume (SiO_2) a by-product obtained from Ferro silicon industries was chosen as the other mineral admixture and is obtained from Oriental Exporters, Navi Mumbai, Maharashtra. The particle size of silica fume was analyzed using PSA and the chemical composition of the micro-silica was found using XRF. The results are shown in Table 1.

Fig. 1 Ball mill used for grinding ceramic tiles

Table 1 Chemical composition of Cement, Ceramic Powder and SF

Formula	Cement (%)	Ceramic Powder (%)	SF (%)
SiO_2	24.3	55.80	97.36
MgO	0.4	4.28	0.79
Al_2O_3	0.6	19.13	0.53
SO_3	3.2	0.54	0.51
K_2O	-	1.36	0.29
Fe_2O_3	6.1	7.88	0.15
CaO	65.4	7.85	0.14
P_2O_5	-	0.13	0.09
Na_2O	-	1.17	0.06
Cl	-	0.13	0.02
MnO	-	0.04	0.01
TiO_2	-	1.31	0.01
Cr_2O_3	-	0.05	100 ppm
ZnO	-	0.10	70 ppm
CuO	-	0.04	51 ppm
Ru	-	90 ppm	47 ppm


Fig. 2 Ceramic before and after grinding in Ball Mill

River sand was used as fine aggregate and the aggregate passing through 16 mm sieve and retained on 12.5 mm sieve was used as coarse aggregate and the type of coarse aggregate used in the concrete mix is granite. Specific gravities of cement, ceramic powder, silica fume, sand and coarse aggregate are 3.16, 2.18, 2.2, 2.65 and 2.75 respectively. CONPLAST SP 430, a commonly available super plasticizer obtained from FOSROC Company was used fully in this research work to obtain the workable concrete mix.

2.2 Mix design

A high strength concrete of M50 grade has been adopted for the present work and the mix design was arrived by ACI method. A total of 4 combinations were prepared for the present research work namely Control, C5, C10, and C15 by partially replacing cement with fine ceramic powder in 0, 5, 10 and 15 percentages respectively. Table 2 and Table 3 show the mix proportion and mix designation details. The results were also compared with previous works done by the author (Chidambaram *et al*. 2015, Srikanth *et al*. 2015) with a ternary blended mix made using ceramic powder and silica fume as supplementary cementitious materials in which Ceramic powder was added in a large proportion of 4, 9 and 14 percentages to encourage waste utilization in construction and silica fume was added in a minor amount of 1% uniformly to all mixes to initiate the pozzolanic reactions. The mixes were designated as C4MS1, C9MS1, and C14MS1.

Table 2 Material proportions

Parameters	Mix Designation						
	Control	C5 /MS5	C10 /MS10	C15 /MS15	C4MS1	C9MS1	C14MS1
Cement, kg/m^3	522.57	496.44	470.31	444.18	496.44	470.31	444.18
Ceramic Powder, kg/m^3	-	26.13	52.26	78.38	25.085	50.17	75.24
Silica fume, kg/m^3	-	26.13	52.26	78.38	1.045	2.09	3.14
Fine aggregate, kg/m^3	544.18						
Coarse Aggregate, kg/m^3	1113.84						
Water, *l*/m^3	182.9						
Super-plasticizer (*l* per 100 kg of cement)	1.5						
w/c	0.29						
Mix ratio	1:1.04:2.13						

Table 3 Designations of mix combination used in this research

Sl.No	Material	Designation	% replacement of cement
01	Concrete with 5% Ceramic powder	C5	5
02	Concrete with 10% Ceramic powder	C10	10
03	Concrete with 15% Ceramic powder	C15	15
04	Concrete with 5% Micro silica	MS5	5
05	Concrete with 10% Micro silica	MS10	10
06	Concrete with 15% Micro silica	MS15	15
07	Concrete with 4% Ceramic powder & 1% Micro silica	C4MS1	5
08	Concrete with 9% Ceramic powder & 1% Micro silica	C9MS1	10
09	Concrete with 14% Ceramic powder & 1% Micro silica	C14MS1	15

Fig. 3 Specimens for corrosion test

2.3 Specimen details, curing environment and methods

Concrete cubes and cylinders were cast to study the strength and durability characteristics of the specimens. Cubes of size 100 mm×100 mm×100 mm were cast to study the compressive strength parameters when cured in normal water and also to check the rate of deterioration when exposed to aggressive environment. BS 1881 (1983) guidelines were used for casting cube specimens. 100 mm×200 mm cylinders were cast to study the tensile strength capacity of the concrete. Water absorption capacity and resistance to permeability were checked using cylinder specimens of size 100 mm×50 mm. To measure the corrosion rate of reinforced concrete, cylinders of size 60 mm×120 mm (1:2 ratios) with steel bars embedded in it at the center as shown in Figure 3 were cast.

2.4 Curing environment

2.4.1 Acids

Since sulphate attack is considered as one of the most common factors for deterioration in concrete, leading to severe damages such as cracking, expansion of concrete and disintegration of cement paste (Guneyisi *et al*. 2010), behavior of the specimens under acid attack were studied in the present work. To assess the behavior of normal concrete and ceramic concrete in aggressive industrial environment and also study the effect of sulphate attack on concrete, the specimens were subjected to curing in diluted H_2SO_4 acids, which the structures are encountered frequently in industries. 1% H_2SO_4 acid was used in this work to observe the deterioration of concrete when cured in it.

2.4.2 Bases

Severe durability problem occurs in marine environment due to chloride attack (Pradhan 2014). To simulate the effect of marine environment and to study their behavior in aggressive marine environment, 5% sodium chloride was used in this study for curing the concrete specimens

2.5 Testing methods

To assess the strength of the high strength concrete cubes cast using ceramic powder as partial replacement, compression strength and split tensile strength tests were performed using an automatic compression testing machine with a capacity 3000 kN. To study the resistance of the structure against the deterioration and to measure the corrosion rate in reinforced concrete structures, many durability tests that stimulate the actual field deterioration mechanisms are available but all are time consuming (Santhosh *et al*. 2014). The ability of resistance against capillary suction was determined as per ASTM C1585. In this method, specimens of 100 mm diameter and 50 mm height cylinders were prepared and were placed in the environmental chamber at a temperature of 50℃ for 3 days. After the 3 days, it was placed inside a sealable container. Then the specimen was kept at 23℃ for 15 days before the start of the absorption procedure. All the surfaces were coated with epoxy resin except bottom surface. Bottom surface was exposed to water. Then the mass of the specimen was noted at different intervals of time. Volume of permeable pores was assessed by the method prescribed by ASTM C642. This test method was used to determine density, percent absorption, and percent voids in hardened concrete. As per this method, the volume of specimen shall be not less than 350 cm^3. After removing from the mould, the specimen was kept at a temperature of 110℃ for 24 h in hot air oven. Then it was kept at a temperature of 25℃ and mass was determined. Then it was immersed in water at 21℃ for 48 h and the mass was taken. Then the specimen was boiled in tap water for 5 h and cooled for 14 h to a final temperature of 25℃. Finally specimen was suspended into water and the mass was determined. Substituting the values of mass in different conditions in the formula, the volume of voids and water absorption was determined. Testing corrosion in reinforced concrete by half-cell potential method as mentioned in ASTM C876-91 was done. In this test initially the values obtained in half-cell potential will be positive for the specimens which indicates, that the specimen has not yet corroded or yet to be corroded. When corrosion starts the value will become negative. The value will be very high initially and will slowly decrease and reach the negative value.

3. Results and discussion

3.1 Compressive strength

3.1.1 Effect of silica fume

It was observed from the average values of the specimens shown in Fig. 4 that the specimens with MS showed a much less strength value when compared with ceramic and control specimens. The minimum strength of ceramic used concrete was for C5 specimens which yielded a strength of 55.42 MPa which is almost nearer to control

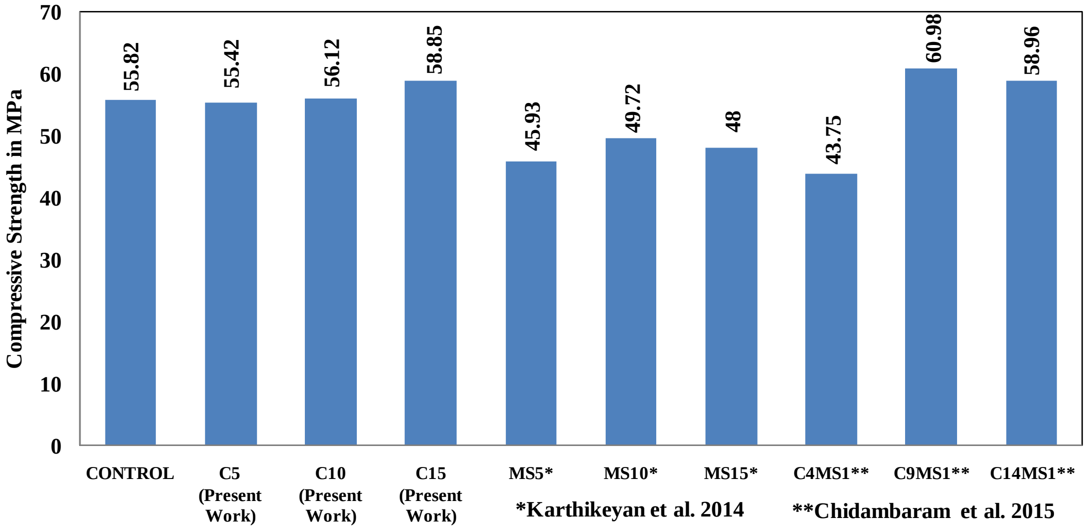

Fig. 4 Average compressive strength of specimens cured in water

concrete strength of 55.82 MPa and less only by 0.97% whereas, MS5 cubes yielded only 45.93 MPa after 28 days curing which is 17.72% less than control cubes and 17.12% less than C5 specimens. Similar decrease in strength by 10.93% and 14% respectively were observed for MS10 and MS15 specimens compared with control specimens. Also, the strength of MS mixed concrete specimens was less by 10.28% and 13.4% for MS10, MS15 specimens than the C10, C15 specimens.

3.1.2 Effect of ceramic powder

On comparing the 28 day strength average results of control and specimens with ceramic powder as mineral admixture shown in Fig. 4 much difference is not noticed. All the mixes (C5, C10, and C15) returned values which are almost nearer to the control specimen values and had negligible difference. The pozzolanic activity of waste ceramic powder is very much less than that of silica fume, for increase in strength in concrete, in addition to filling ability the material should also possess a good pozzolanic activity. This is achieved well when both ceramic powder and silica fume were used as mineral admixtures (ternary blended). The waste ceramic powder which is product obtained from broken tiles, had come across many processes that are meant for tiles usage and have less pozzolanic reaction compared to silica fume, so the it affects the strength in concrete, when a proper binding material like cement is replaced. But, it can be seen that the strength is not less than the target mean strength. The strength of control was found to be 55.82 MPa, C5 specimens showed a decrease in strength by 0.97%, C10 specimens showed a slight increase in strength by 0.23%, whereas C15 specimens showed an increase of 6.2%. But all have crossed the mean target strength limit and it is noticed that the waste ceramic tiles remain as an inert material, neither has it taken part in the reaction nor it reduces the strength of concrete when replaced for cement. The strength characteristics got increased when the replacement percentage was increased. The usage of cement can be reduced by replacing with waste ceramic tiles powder in minimal as the strength characteristics are not disturbed.

3.1.3 Effect of ternary blended mix

A decent increase in strength of 60.98 was obtained for C9MS1 specimens as reported by Chidambaram *et al*. (2015). Ceramic powder when used solely as mineral admixture showed moderate results with neither increase nor decrease in strength compared with control specimens. When both the mineral admixtures (Silica fume, ceramic powder) were used individually, they will satisfy only the part in which they are stronger. For example silica fume can initiate pozzolanic reaction and ceramic powder can act as a filler agent there by imparting strength to concrete. In ternary blended mix (Ceramic powder+silica fume), the mix has been arrived such that the mineral admixtures should act as a pozzolanic agent as well as filler agent. So, ceramic powder acted in this mix as a filler agent and silica fume is the pozzolanic admixture. So the strength in ternary blended mix was higher than those of mixes made with only silica fume or only ceramic powder. The strength results of ternary mix especially C9MS1 and C14MS1 are apparent that they can contribute to increase in strength by 8.5% and 5.33% than control concrete.

3.1.4 Compressive strength overall view

Fig. 4 shows the compressive strength of specimen cast with ceramic powder, silica fume and ternary blended mixes. It is clear that ternary blended mix (C9MS1) showed a higher strength of 60.98 MPa. Though all mixes have reached strength beyond the mean target strength required for M50 concrete it is observed from the results that mixes containing ceramic powder as mineral admixture both in binary and ternary blended form, recorded higher strength than specimens with silica fume. Also the ternary blended mix showed better early age strength which is understood from Fig. 4. They impart strength to concrete by ceramic powder being involved in filling pores present in the concrete and silica fume inducing pozzolanic reactions resulting in better initial strength increase. The pozzolanic

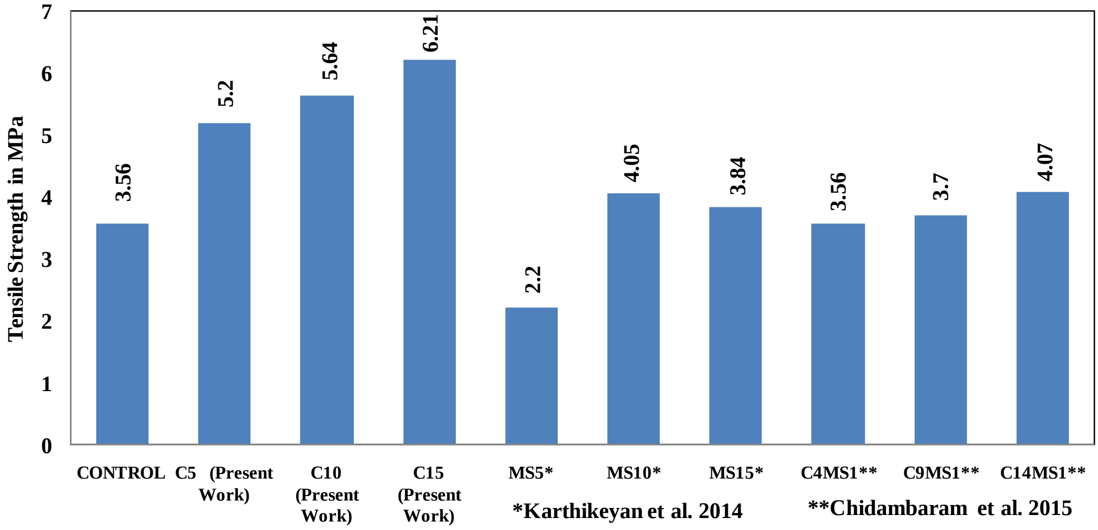

Fig. 5 Average tensile strength of specimens cured in water

activity of waste ceramic powder is very much less than that of silica fume. For increase of strength in concrete, in addition to filling ability, the material should also possess a good pozzolanic activity. This is achieved well when both ceramic powder and silica fume were used as mineral admixtures (ternary blended). The waste ceramic powder which is product obtained from broken tiles, had come across many processes that are meant for tiles usage and has less pozzolanic reaction compared to silica fume, so it affects the strength in concrete, when a proper binding material like cement is replaced. But, it can be seen that the strength is not less than the target mean strength.

3.2 Tensile strength

3.2.1 Effect of silica fume

The average values of tensile strength values of specimens cast with silica fume as a partial replacement material are shown in Fig. 5. It is understood from the results that silica fume when used in very less quantity of about 5% showed a minimum strength of 2.2 MPa which is less than control by 38.2%. MS 10 registered a reasonable value of 4.05 which is 13.76% more than control and a 7.86% increase was shown by MS15 with strength being 3.84MPa. It is clear that the very fine silica fume particles when added to cement in smaller percentages does not contribute much in increasing the tensile strength.

3.2.2 Effect of ceramic powder

Ceramic powder added specimens showed a very high tensile strength of 5.2MPa, 5.64MPa and 6.21MPa which is more than 46.07%, 58.42 % and 74.44 % for C5, C10 and C15 respectively than the control concrete and is reported in Fig. 5.

3.2.3 Effect of ternary blended mix

Fig. 5 shows the tensile strength of ternary blended mix, with ceramic powder and silica fume as mineral admixtures was already discussed in Chidambaram *et al*. (2015). It is observed that the strength values were more for C14MS1 specimen and all the values were neared to the strength of control specimen.

3.2.4 Tensile strength-overall view

On comparing the tensile strength of specimens shown in Fig. 5 it can be observed that ceramic powder mixed cement concrete specimens showed a considerable increase than the mixes. MS5, MS10 and MS15 showed a major decrease in strength by 57.7%, 22.9% and 26.1% than C5 which has registered the lower tensile strength among the ceramic powder mixed concrete specimens. The tensile strength indirectly reflect the compressive strength characteristics and it is noted that both in compressive strength and tensile strength for the specimens with ceramic powder, there was a gradual increase as the percentage of replacement was increased. Though the tensile strength of ternary blended mix was decent, they could not match with that of specimens in which only ceramic powder was used as partial replacement, since several parameters affect the concrete during mixing, such as, the air content, voids presence, Non uniform distribution of aggregates, they may affect the strength some times and the major inference obtained from the output is only reported here. Here also the strength of C4MS1, C9MS1 and C14MS1 specimens showed a considerable decrease by 31.53%, 28.85% and 21.74% than C5 which has the lowest tensile strength in ceramic powder made specimens.

3.3 Resistance to deterioration in aggressive environment

3.3.1 Effect of silica fume in resisting deterioration

The results shown in Fig. 6 and Fig. 7 as reported by Srikanth *et al*. (2015) indicate that specimen with silica fume replacement are also showing better resistance to deterioration when exposed to acid or alkali media compared with control specimens. Least deterioration of 20.79% was shown by MS5 specimen in H_2SO_4 medium. In the alkali medium also the same trend can be seen where the percentage of deterioration was 18.39 for MS5 and it

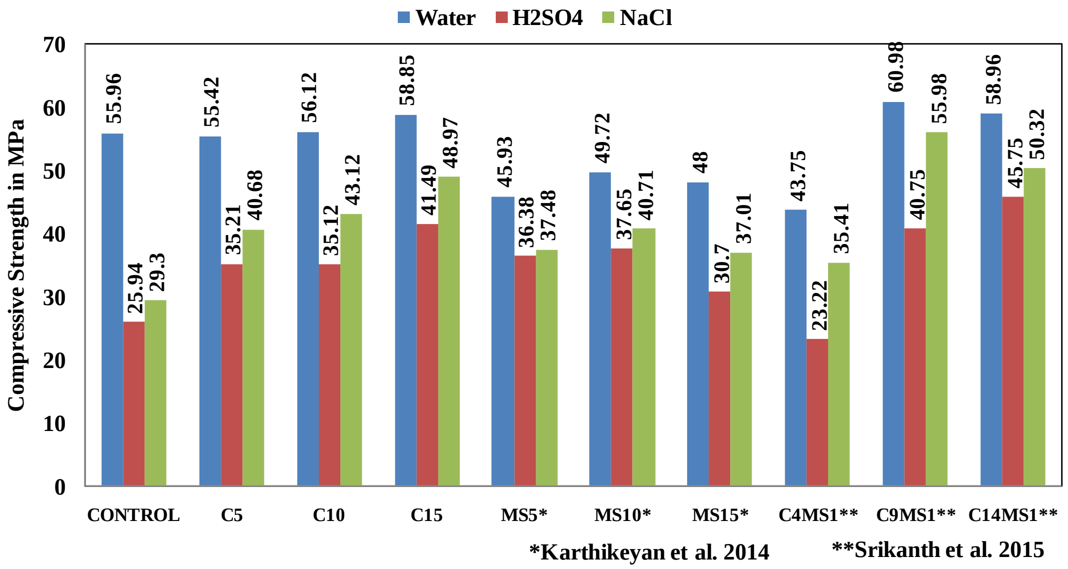

Fig. 6 Average strength of cubes in different curing environment

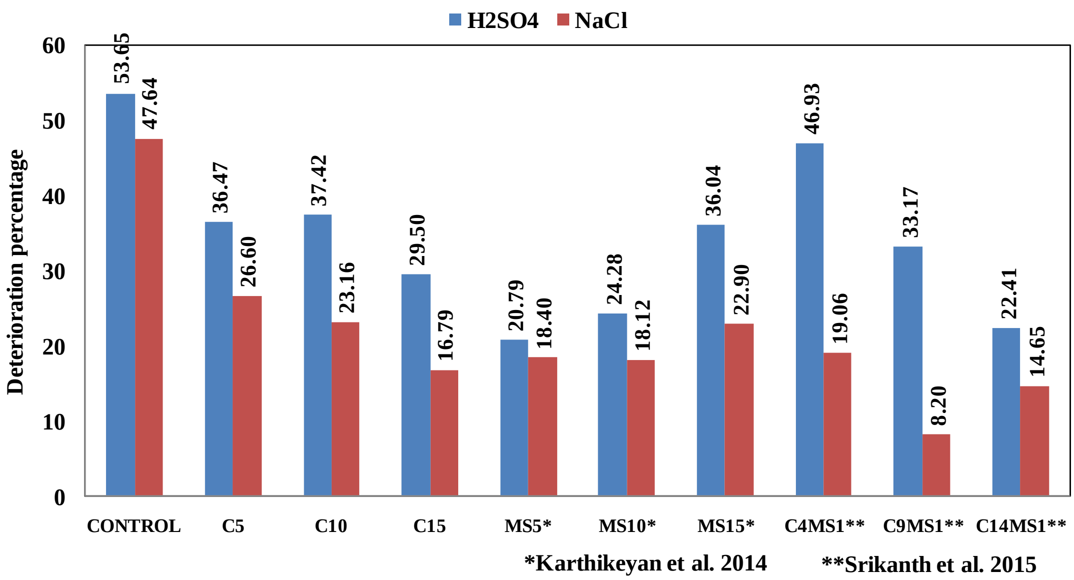

Fig. 7 Deterioration rates of specimens

reduced to 18.12 for MS10 which is not a major reduction and for MS15 the deterioration got increased to 21.24%. The specimens were able to resist deterioration along with cement when only small amount cement was replaced and when the replacement level increases support from cement got reduced and also the mineral admixtures due to the fine size got dissolved in acid or alkali environment making the specimen weak leading to deterioration.

3.3.2 Effect of ceramic powder in resisting deterioration

Fig. 6 and Fig. 7 illustrate the strength and deterioration of ceramic powder mixed concrete cubes. It is evident that control has corroded most by 53.65% and 47.64% in acid and alkali medium respectively. Among specimen with ceramic powder, C10 deteriorates more by 33.88% and 18.83% in the aggressive environment whereas C5 showed a less deterioration of 22.02% in acid medium and 9.09% in NaCl medium making it best suited for structures in industrial and marine environments, but the compressive strength value of C5 in normal water environment is and it is C15 which has shown more strength of 58.85 MPa in normal environment and a nominal deterioration rate of 29.5% and 16.79% in aggressive environment.

3.3.3 Effect of ternary blended mix in resisting deterioration

On observing the rate of change of deterioration shown in Fig. 6 and Fig. 7 as reported by Srikanth *et al*. (2015), it can be noticed that the percentage of deterioration decreases with increase in replacement percentage. A higher deterioration of 46.93% was observation for C4MS1 and it reduced to 33.17% and 22.41% for C9MS1 and C14MS1 respectively in H_2SO_4 medium. However in NaCl medium

Fig. 8 Specimen after subjected to curing in acid

Fig. 9 HCP tests being performed on specimens

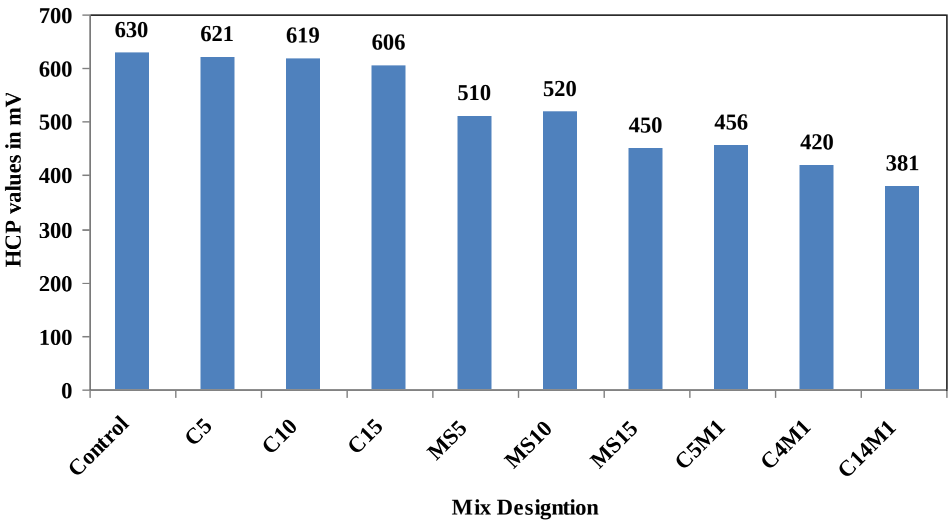

Fig. 10 Average corrosion rate of specimens cured in H_2SO_4

C9MS1 recorded a lower deterioration of 8.19% whereas C4MS1 and C14MS1 showed much higher deterioration of 19.06% and 14.65%.

3.3.4 Overall comparison

Control specimen deteriorated more, specimens with waste ceramic powder replaced in 5% for cement showed better resisting capabilities of 22.02% and 9.09% in both acid and base media respectively. Fig. 8 shows the deteriorated image of the concrete cured in acid. When the ceramic powder percentage was increased the deterioration faced was slightly more. Regarding specimens with silica fume as mineral admixtures it was found that the rate of deterioration increased when the replacement levels were increased and the trend was found to be reversed in ternary blended mixes where the deterioration was lower replacement levels and less for higher replacement levels. Though C9MS1 registered a lower deterioration rate of 8.19% in NaCl medium it failed in acid resistance showing a higher rate of 33.17%, Though C5 has performed well both in acid and base medium, its strength in normal environment is low and C15 has performed well in normal, acid and alkali environment with strength of 58.85 MPa and a deterioration of 29.5% and 16.79% in aggressive environment.

3.4 Corrosion of rebar in concrete

3.4.1 Effect of ceramic in resisting corrosion of rebar

Fig. 9 shows the half-cell potential test being conducted on specimens. The average corrosion values measured in mV after two months curing of the specimens in different mediums are shown in Fig. 10 and Fig. 11. It can be observed that the highest values were for control specimen indicating that the steel in control concrete has corroded much than those with mineral admixtures in both acid and alkali medium. Specimens with ceramic powder as mineral admixtures showed a gradual decrease in rate of corrosion as the percentage of the mineral admixture is increased, i.e., a higher rate of -673 mV can be seen for C5 specimen and the rate gradually decreased to -636 mV and -615 mV for C10 and C15 specimens in acid medium, similar trend was observed for specimens in alkali medium with C5 registering a higher corrosion rate of -621 mV and C10, C15 showing a corrosion rate of -619 mV and -606 mV.

3.4.2 Effect of silica fume in resisting corrosion of rebars

Specimen with MS as mineral admixture showed much less values than those with ceramic. MS15 had the higher corrosion rate of -630 mV in acid medium and MS10 had

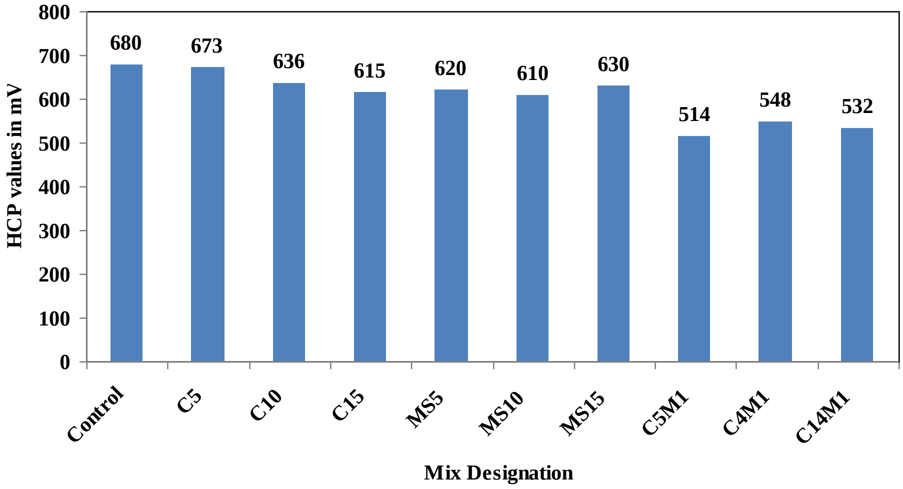

Fig. 11 Average corrosion rate of specimens cured in NaCl

Table 4 Standard deviation values of the experimental results

Mix	Standard Deviation in MPa				Standard Deviation in mV	
	Compressive Strength in Normal Environment	Tensile Strength in Normal Environment	Compressive Strength in H2SO4	Compressive Strength in NaCl	Corrosion in H2SO4	Corrosion in NaCl
Control	1.12	0.07	0.52	0.59	13.60	12.60
C5	0.83	0.08	0.53	0.61	10.09	9.31
C10	0.56	0.06	0.35	0.43	6.36	6.19
C15	1.47	0.16	1.04	1.22	15.38	15.15
MS5	0.23	0.01	0.18	0.19	3.10	2.55
MS10	0.70	0.06	0.53	0.57	8.54	7.28
MS15	1.06	0.08	0.68	0.81	13.86	9.90
C4MS1	0.44	0.04	0.23	0.35	5.14	4.56
C9MS1	0.91	0.06	0.61	0.84	8.22	6.30
C14MS1	1.30	0.09	1.01	1.11	11.70	8.38

the lower corrosion rate of -610 mV. The variations were minimum in the acid medium ranging from -620 mV, -610 mV, -630 mV for MS5, MS10 and MS15 specimens. In alkali medium the corrosion rates were fluctuating with MS5 and MS10 possessing a -510 mV and -510 mV respectively and MS15 was showing a much reduced value of -450 mV.

3.4.3 Effect of ternary blended in resisting corrosion of rebars

Ternary blended mixes show better resistance to corrosion which is evident from Fig. 10 and Fig. 11. C9MS1 sows a higher corrosion rate of -548 mV which is even far lower than the control specimen or those with ceramic and silica fume mineral admixtures in acid medium. Lower corrosion rate was observed for C14MS1 by -514 mV. In alkali medium also the performance of ternary mixes was good and a lower corrosion rate of -381 mV was able to achieve for C14MS1 specimen. In general it can be seen that the overall performance of ternary blended mixes were good in resisting corrosion than the other mineral admixtures. It is due to the proper filling of the pores and resistance to penetration by the ternary blended mixes.

Standard deviation for all the tests related to compressive strength, tensile strength, deterioration and corrosion are tabulated in Table 4.

3.5 Water absorption test

It is reported by Khatib *et al*. 2004 that when metakaolin was used as a mineral admixture, the water absorption values ranged between 4.2% and 5.4%. Similarly, in another study, Razak *et al*. (2004) reported that when silica fume was used as a mineral admixture, the absorption values varied between 2.9% and 4.8%. Fig. 12 shows water absorption test being conducted. On observing the average water absorption characteristics of ceramic powder mixed concrete specimen shown in Table 5, it was found that C15 has absorbed water less of about 0.88% and C5 has more water absorption by 1.35%. These details reflect the strength characteristics shown in Fig. 4 from which it was evident that C15 has exhibited more strength of 58.8 MPa than C5 or C15 which is due to the presence of less percentage of voids and water absorption characteristics.

All the silica fume based specimens showed a very less water absorption by 0.34%, 0.383% and 0.52% for MS5, MS10 and MS15 specimens. Silica fume being very fine,

Table 5 Percentage of water absorption

Specimens	Percentage of average water absorption
CONTROL	1.25
C5	1.35
C10	1.25
C15	0.88
MS5	0.34
MS10	0.383
MS15	0.52
C4MS1	3.33
C9MS1	1.18
C14MS1	0.72

Fig. 12 Specimens being tested for water absorption

has contributed in filling the pores effectively but initial strength was nominal as it remains inert imparting less pozzolanic actions at the initial stage. The entire silica fume mixed specimens showed a very less water absorption by 0.34%, 0.383% and 0.52% for MS5, MS10 and MS15 specimens Ternary blended mix showed better resistance to water absorption by 3.33%, 1.18% and 0.72% for C4MS1, C9MS1, C14MS1 mixes respectively and all are found to be within the limit. The combined filling and pozzolanic characteristics of silica fume and ceramic made it better to resist the water absorption. On comparing the water absorption results of binary blended mix specimens with silica fume alone as mineral admixtures and ternary blended mix with both ceramic powder and silica fume as mineral admixtures with compressive strength values shown in Fig. 5 it can be noted that the strength values are better for MS10 and C9MS1, though MS5 and C14MS1 specimens showed a very little water absorption, since the replaced proportions of mineral admixtures have either dissolved when added in minor quantity or unable to provide necessary pozzolanic activity when added in a larger proportion.

3.6 Percentage of voids

Fig. 13 shows the total percentage of voids present in each mix after conducting the porosity test. Presence of 14.7865 % voids was reported for C4MS1 making it the specimen with larger percentage of voids. Specimens with waste ceramic powder as mineral admixtures have shown reasonable reduction of voids, increasing the percentage of

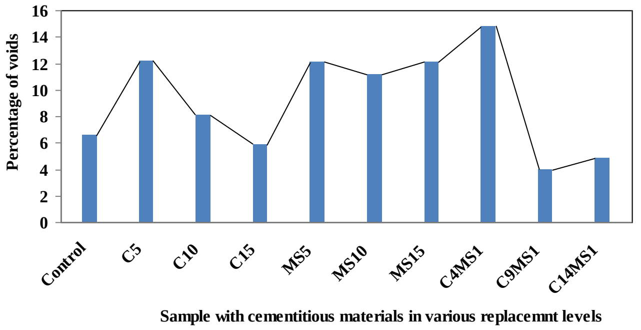

Fig. 13 Volume of voids in percentage

replacement resulted in decreasing the percentage of voids to 8.1% and 5.86% for C10 and C15. Percentage of voids with silica fume as admixture was uniform and the variation is less. Among the ternary blended mix, C9MS1 and C14MS1 registered less percentage of voids with C9MS1 showing only 3.92% of pores.

4. Conclusions

Based on the experimental investigations carried out, following conclusions were arrived:

- All mixes with ceramic powder as supplementary cementitious material either in binary or in ternary combinations, have reached strength beyond the mean target strength required for M50 concrete.
- The same trend was seen while comparing the tensile strength characteristics of the specimens with ceramic powder made concrete specimens registering a much higher value than other mixes.
- C15 registered strength of 59.85 MPa in binary combination and C9MS1 showed a higher strength of 60.98 MPa among ternary mixes. When the ceramic powder percentage was increased, the deterioration faced got reduced. When cured in aggressive environment, control specimen deteriorated more, C15 showed better resistance to deterioration by 29.5% and 16.8% in both acid and base media respectively.
- Specimens with ceramic powder as mineral admixtures showed a gradual decrease in rate of corrosion as the percentage of the mineral admixture is increased, i.e., a higher rate of -673 mV can be seen for C5 specimen and the rate gradually decreased to -636 mV and -615 mV for C10 and C15 specimens in acid medium, similar trend was observed for specimens in alkali medium with C5 registering a higher corrosion rate of -621 mV and C10, C15 showing a corrosion rate of -619 mV and -606 mV.
- Water absorption characteristics of ceramic powder mixed concrete specimen reveal that C15 has absorbed water less of about 0.89% and C5 has more water absorption by 1.35%. Ternary blended mix showed better resistance to water absorption by 3.33%, 1.18% and 0.72% for C4MS1, C9MS1, C14MS1 mixes respectively and all are found to be within the limit.
- Specimens with waste ceramic powder as mineral

admixtures have shown reasonable reduction of voids, increasing the percentage of replacement resulted in decreasing the percentage of voids to 8.1% and 5.86% for C10 and C15.

• In general it is observed that presence of ceramic powder as a partial replacement proved to be a better replacement material as it performs well in normal and aggressive environment possessing better strength, durability and corrosion resisting properties.

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