CHAPTER 6
Utilization of Fly Ash and Copper Tailings in Concrete

6.1 Introduction

The construction industry is considered as a backbone of infrastructure development. The disposal of anthropogenic waste materials coming from different types of industries will lead to a severe environmental threat regarding the contamination of surrounding soil, air, and groundwater. This problem has encouraged the researchers to explore the possible ways about the disposal and recycling of these wastes. Usage of these anthropogenic wastes in the construction industry is one of the promising options to surmount this alarming issue.

Copper is one of the most useful metal with high electric and thermal conductivity and less corrosive property. It is well known for its ability to make alloys and high malleability. Being the most used metal, the demand is increasing with the population. This everlasting and increasing demand escalated the manufacturing of copper, which accounts to be about 21 million tons in 2018 (USGS MCS, 2019). CT is one of the significant wastes generated during the manufacturing of copper, which is generated at the floatation and concentration stages in the process of copper extraction. There are about 128 tons of copper tailings generated in the production of each ton of copper (Gordon, 2002; Beniwal et al., 2015). The tailings generally contain Aluminum, Cadmium, Iron, Silica, Lead, Magnesium, Zinc, different oxides, hydroxide, and other materials, which may adversely impact the environment and human health of the vicinity of the dumping sites (Yang et al., 2013; Kundu et al., 2016).

Many researchers (Dudka and Adriano, 1997; Rösner, 1998; Castilla, 1996; Sharma and Al-Busaidi, 2001) have highlighted the ill-effects of copper tailings on the surface and groundwater, surrounding soil, vegetation, and aquatic life, which further adversely affect the other living bodies. In this regard, there is a great need to surmount this problem by giving efficient, sustainable, and scientifically proven solution by either utilizing copper tailings or by recycling. Many possibilities have been investigated, and solutions are proposed by the researchers to make the tailings productive. Onuaguluchi and Eren (2012) replaced cement with copper tailings to make high conductivity concrete and recommended it for making easy ice removable roads. Gupta et al. (2012) tested the clayey soil stabilization property of copper tailings and suggested that a mixture of 30% copper tailings and 70 % clayey soil give good bearing capacity. Some of the researchers (Gupta et al., 2016; Beniwal et al., 2015) have used CT as a partial replacement of fine aggregates in concrete. Ahmari and Zhang (2012) examined the utilization of copper tailings to develop eco-friendly bricks. Besides this, the feasibility of utilizing it as a partial replacement of cement is studied in a few of the research works (Kundu et al., 2016; Onuaguluchi and Eren, 2016). An abundant amount of FA and CT are spread in the valuable land and polluting the surrounding environment. The usage of FA as a pozzolanic additive in concrete is stared as early as 1914 (Halstead, 1986) and now it has been extensively used in cement industry due to its inherent pozzolanic property.

In the earlier chapter, the effect on the environment by the concrete produced by partial replacing of cement combinedly with FA and CT has been assessed using LCA analysis. Along with LCA, economic aspects of the modified concrete have also been evaluated. Following are different positive aspects where the results of comparative analysis of concrete manufactured after partially replacing the cement with FA and CT are useful:

A. It reduces the cement requirement of the construction industry and then, minimizing pollution during the cement manufacturing process.

B. The heaps of FA and CT spread all over the world can be utilized and will be beneficial to the surroundings to maintain a better environment.

C. The modified concrete is economically beneficial for construction in the industry.

D. This process vacates the valuable landfill sites filled by the waste that can be utilized for other productive purposes.

In the current chapter, the strengths of the modified concrete mix proportions are identified. The complete methodology adopted in this study is summarized in Fig. 6.1. Initially, materials (FA and CT) were collected, which were characterized to assess the feasibility of the samples as per the ASTM requirement. The subsequent sections explain more insight into the methodology adopted in the proposed study.

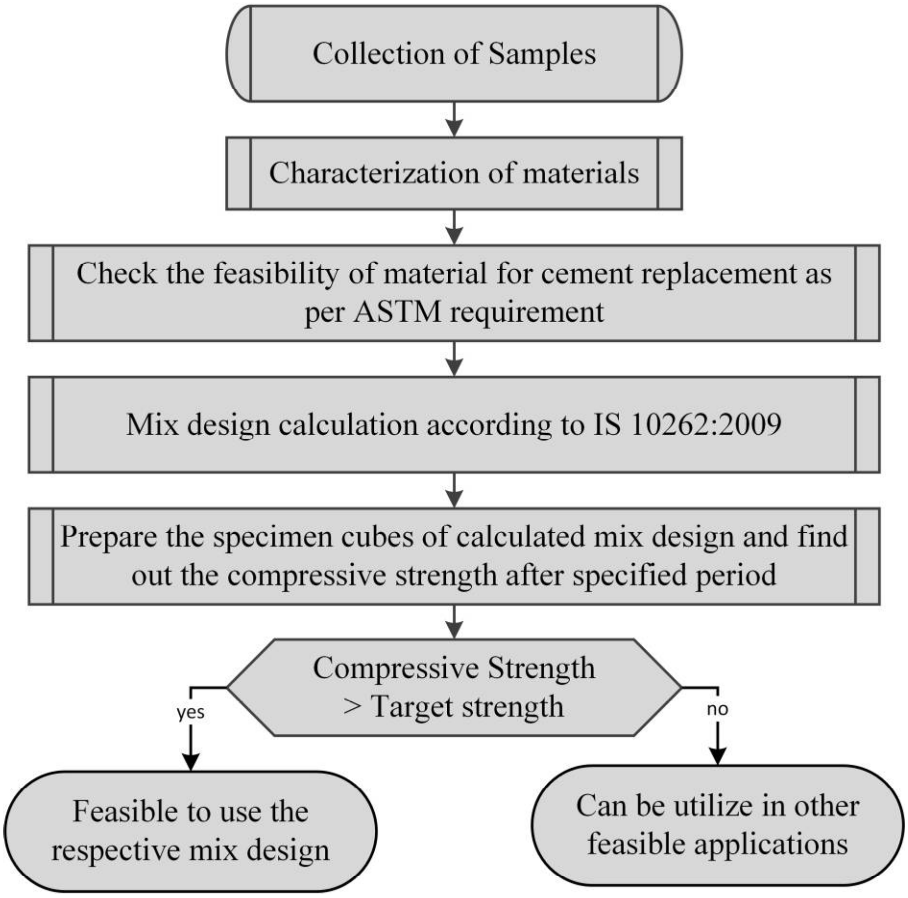

Fig. 6.1 Processed follows for the compressive strength assessment of modified concrete

6.2 Feasibility of FA and CT in Concrete

XRF results (presented in Table 6.1) shows that both, FA and CT, are composed of pozzolanic materials (SiO_2, Al_2O_3, and Fe_2O_3) with a small amount of CaO, MgO, and other compounds. ASTM C 618 classified FA into two categories (i.e., Class C and Class F). Both are enriched with SiO_2, Al_2O_3 and Fe_2O_3 with nearly 50% in Class C and around 70% and higher in Class F fly ash. The combined weight of pozzolanic materials found in FA and CT is 96.1% and 86.93% of their weights, respectively. These values are considerably higher than the recommended value (70%) given in ASTM C618-19 standard and make them suitable to use in concrete by partially replacing cement.

The morphology of FA, CT, and cement identified by SEM results, as presented in chapter 3, shows that the FA particles are spherical in shape. It applies a greasy effect to the concrete due to its ball bearing like behavior, resulted in a better workable concrete, which is easier to pump, as the spherical particle reduces the internal friction between ingredients of concrete. Replacing cement with FA of similar weight and lesser density leads to a reduction in concrete bleeding due to less water requirement and a higher volume of fine particles. Use of irregularly shaped copper tailing particles with cement (having nearly equivalent particle size) may exhibit higher interlocking capability, increase the density of concrete and impart additional strength when it combines with the cement and FA particles.

Table 6.1 Chemical composition and physical properties of cement, copper tailings and fly ash

Chemical/ physical parameter	OPC Grade 43	CT	FA	Requirement (as per ASTM C 618)
SiO_2 (%)	20.27	65.19	69.26	-
Al_2O_3 (%)	5.32	8.81	23.51	-
Fe_2O_3 (%)	3.56	12.93	3.33	-
$SiO_2 + Al_2O_3 + Fe_2O_3$(%)	29.15	86.93	96.10	70.00 min
CaO (%)	60.41	1.48	0.51	-
MgO (%)	2.46	3.98	0.62	5.00 max
SO_3 (%)	3.17	-	-	5.00 max
K_2O (%)	-	0.92	1.14	
TiO_2 (%)	-	0.30	1.03	
Loss on ignition (%)	1.87	2.00	2.3	6.00 max
Moisture (%)	0.20	0.15	0.30	3.00 max
Specific Gravity	3.15	3.20	2.10	-
Particle size (μm)	50-90	40-100	20-80	-
Bulk density (kg/m^3)	1270	1420	940	-

After the addition of water to cement, the exothermic hydration reaction will initiate, and it leads to the release of lime. Although the role of lime is well known, the additional release will impart porosity to the structure. This imparted porosity will develop microcracks, degradation in bond strength, and put an adverse effect on the concrete durability. The phenomenon is likely to be more predominant in the case of higher-grade concrete. The combined utilization of fly ash and copper tailings have the potential to overcome this problem due to the presence of pozzolanic ingredients. The behaviour of additional pozzolanic material on the strength of the concrete is detailed in Fig. 6.2. Though, Hewlett (2003) experimented and confirmed that pozzolanic materials (in FA) reacts with excessive lime and improves the strength of the concrete, the combined effect of fly ash and copper tailings on the strength of concrete by partial replacement of cement is a matter of investigation. This has motivated to explore the performance of concrete under such situations. Tricalcium silicate ($C_3S \rightarrow 3CaO.SiO_2$), dicalcium silicate ($C_2S \rightarrow 2CaO.SiO_2$), tricalcium aluminate ($C_3A \rightarrow 3CaO.Al_2O_3$) and tetra-calcium aluminoferrite ($C4AF \rightarrow 4CaO.Al_2O_3.Fe_2O_3$) are the chief minerals phases found in the OPC (Struble et al., 2011). The hardening process of OPC takes place as a result of the reaction between these compounds with water. In the processes of hydration, lime is released, which is a surplus and not utilized in the hardening process (Sharma and Pandey, 1999). This excess lime adversely affected the durability of the hardened concrete due to the formation of microcracks and weakened the bonding with concrete (Massazza, 1998). Addition of pozzolanic material will act as a solution to this problem because such material will react with surplus lime and provide similar binding property as given by the cement.

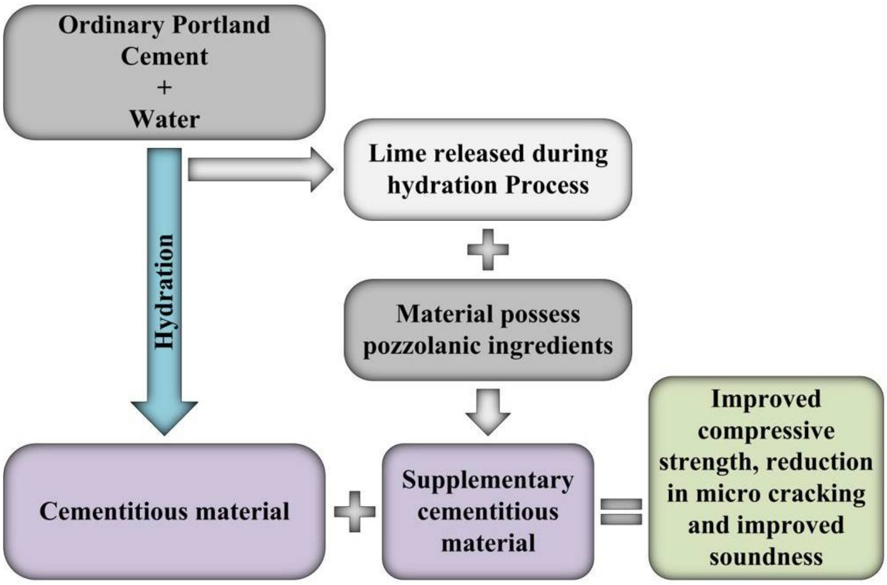

Fig. 6.2 Formation of supplementary cementitious material after the partial replacement of cement with pozzolanic material

6.3 Mix Design of Concrete

Ordinary Portland cement (OPC) of 43 grades complying with IS 8112:2013 and specific gravity 3.15 has been used as a binder. River sand (specific gravity 2.74) confirming to Zone-I of IS 383:2016 has been used as fine aggregate. The crushed stone (specific gravity 2.74) with the proportion of 2:3 of 10 mm and 20 mm size has been taken as coarse aggregate that complying with the IS 383:2016. To increase the workability along with the reduction in water content in the mix design of concrete, ULTRACON 58 HP admixture (specific gravity 1.24) has been used as per IS 9103:1999. Fig 6.3 gives an overview of the materials FA, CT, cement, sand, aggregate used in the preparation of concrete.

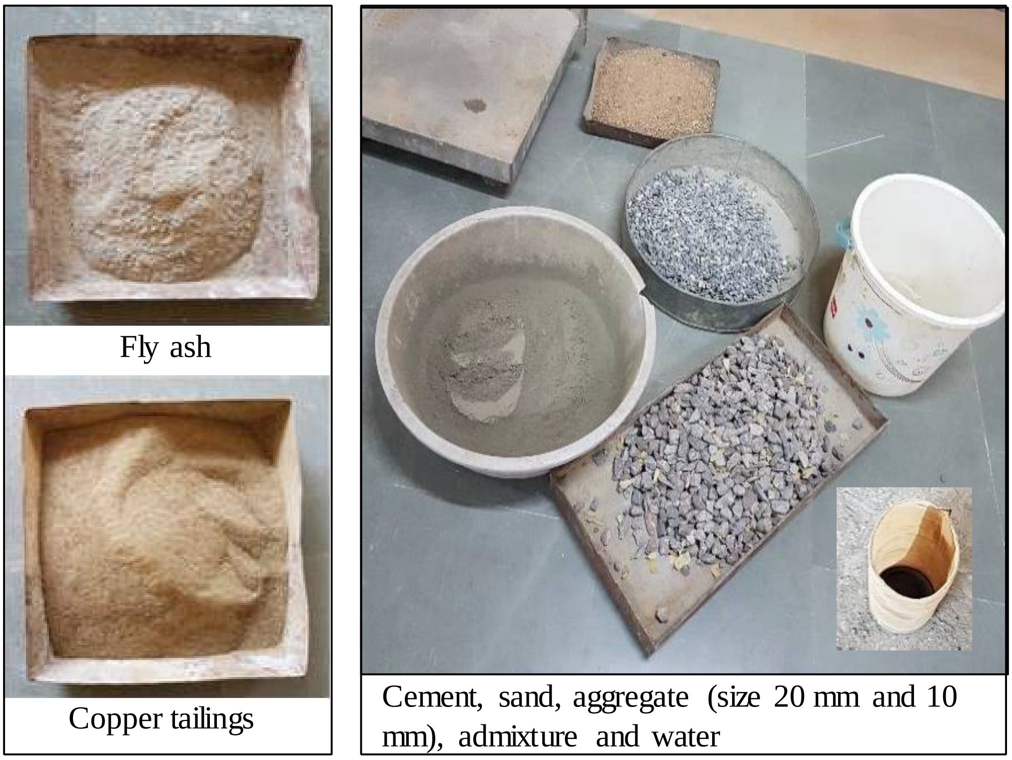

Fig. 6.3 FA, CT, Cement, sand, aggregate, admixture, and water used in the experiment

A total of 14 different mix design proportions were prepared for a target strength of 30 MPa as per IS 10262:2009. These mix proportions have been considered for the casting of 126 cubes of 150 mm size (@ 9 cubes per mix proportion) for two different water-cement (w/c) ratios (i.e., 0.45 and 0.5) according to the guidelines given in IS 456: 2000. For each of the water-cement ratio (out of all mix proportions) one control specimen mix has also been prepared. Considering the view of earlier findings of the researchers and code provisions, FA has been replaced with cement from 10%, 20% and 30% by weight of cement combined with 5% and 10% CT respectively. These mix proportions were labelled as M1 (FA 10% and CT 5%), M2 (FA 10% and CT 10%), M3 (FA 20% and CT 5%), M4 (FA 20% and CT 10%), M5 (FA 30% and CT 5%), and M6 (FA 30% and CT 10%) for two different w/c ratios of 0.45 and 0.5. All mix specimens have been immersed in the water tank for curing purpose for the prescribed duration as the specified code provision. The compressive strengths of the cubes have been measured after 7, 28, and 56 days by a universal testing machine (UTM, capacity 1 ton). The details of the mix design related to all the proportion of copper tailings and fly ash are presented in Table 6.2. Photographs related to the casting of cubes and testing of compressive strength are shown in Fig. 6.4 and Fig. 6.5.

Fig. 6.4 Preparing concrete and casting the cubes

Fig. 6.5 Testing the compressive strength of casted cube

6.4 Results and Discussion

The deformation and stress developed in the casted cubes have been measured after 7-days (A), 28-days (B), and 56-days (C), respectively during the compressive strength tests of all the mix proportions. These results are presented, in the form of 14 graphs, as shown in Fig. 6.6 to Fig. 6.19, which are distinguished by the category of the sample as detailed in Table 6.2. Each figure shows the stress-strain behavior of an individual mix proportion for 7, 28, and 56 days.

Table 6.2 Mix design details of different proportion used for casting concrete cubes

Quantity of water, cement, sand, FA, CT, aggregate, and admixture for M30 cube for 9 cubes of 150 mm size (all values are in kg)											
Category of Sample	Water binder ratio	FA (% of Cement)	CT (% of Cement)	Water	Cement	FA	CT	Admixture	Coarse Aggregate*		Fine Aggregate
									10 mm	20 mm	
M1	0.45	10	5	5.752	10.865	1.278	0.639	0.064	17.643	26.464	28.199
M2		10	10	5.752	10.226	1.278	1.278	0.064	17.645	26.467	28.203
M3		20	5	5.752	9.586	2.556	0.639	0.064	17.507	26.261	27.983
M4		20	10	5.752	8.947	2.556	1.278	0.064	17.371	26.057	27.986
M5		30	5	5.752	8.308	3.835	0.639	0.064	17.371	26.057	27.766
M6		30	10	5.752	7.669	3.835	1.278	0.064	17.374	26.060	27.769
M1	0.5	10	5	5.832	9.914	1.166	0.583	0.058	17.549	26.323	28.517
M2		10	10	5.832	9.331	1.166	1.166	0.058	17.551	26.326	29.251
M3		20	5	5.832	8.748	2.333	0.583	0.058	17.427	26.140	29.045
M4		20	10	5.832	8.165	2.333	1.166	0.058	17.429	26.143	29.048
M5		30	5	5.832	7.582	3.499	0.583	0.058	17.305	25.958	28.842
M6		30	10	5.832	6.998	3.499	1.166	0.058	17.307	25.961	28.845
C-Mix	0.45	Control Mix		5.752	12.782	-		0.064	17.776	26.664	28.413
	0.5			5.832	11.664			0.058	17.668	26.503	29.447

*The coarse aggregate of size 10 mm and 20 mm are taken as 40 % and 60% of the total weight of the coarse aggregate.

These stress-strain curves show non-linear behaviour for all mix proportions, which may be due to non-homogeneity in concrete mass and leads to the differential moment between binding material and aggregate. It is also noted that with the increase in w/c ratio, the strength of the concrete decreases and may result in the development of cracks due to excess in shrinkage.

The cubes of mix M1 to M6 at w/c ratio 0.45 (Fig. 6.6 to Fig. 6.11) show relatively higher strength than cubes of mix M1 to M6 at w/c ratio 0.5. Stress-strain ratio for cubes of mix M1 (w/c ratio 0.45) have been found for different duration concrete, which increases with increase in time duration of concrete (i.e. stress-strain ratio at 56 days > stress-strain ratio at 28 days > stress-strain ratio at 7 days), which have a similar gradient pattern as found in the control mix of w/c ratio of 0.45. A similar pattern has been observed in the case of w/c ratio of 0.5 also. From the analysis of results corresponding to cubes for mix M2 (w/c 0.45; Fig. 6.7), it can be inferred that cubes gain higher compressive strength in 56 days (i.e., M2-C). However, they deformed more as compared to 7 and 28 days (i.e., M2-A and M2-B at w/c 0.45). The cubes under mix M3 and M4 (w/c 0.45; Fig. 6.8 and Fig. 6.9) show nearly similar trends, however, the ultimate strength for M3-B and M3-C is slightly higher than that of M4-B and M4-C. In cube mix of M5 and M6 (w/c 0.4; Fig. 6.10 and Fig. 6.11) there is a considerable deformation observed in cubes M5-B, M5-C, M6-B, and M6-C. For similar stress, cubes under category M1 to M6 (Fig 6.12 to Fig. 6.17) for w/c ratio of 0.5 shows higher strain as compared to cubes of w/c ratio 0.45. The slopes for all three cubes under category M1 at 0.5 w/c ratio, (Fig. 6.12) is higher than those found in the cubes under category M2 at w/c 0.5 (Fig. 6.13). There is less strain observed in 7-days strength (cube no M1-A for w/c 0.5) for similar stress in M2-A, and a similar trend has been found in the M3 and M4 of w/c 0.5 with a progressive reduction in stress. The cubes in categories M5 and M6 of w/c 0.5 are following nearly similar trends; however, in both, variation in strain is higher with the stress value except M5-C.

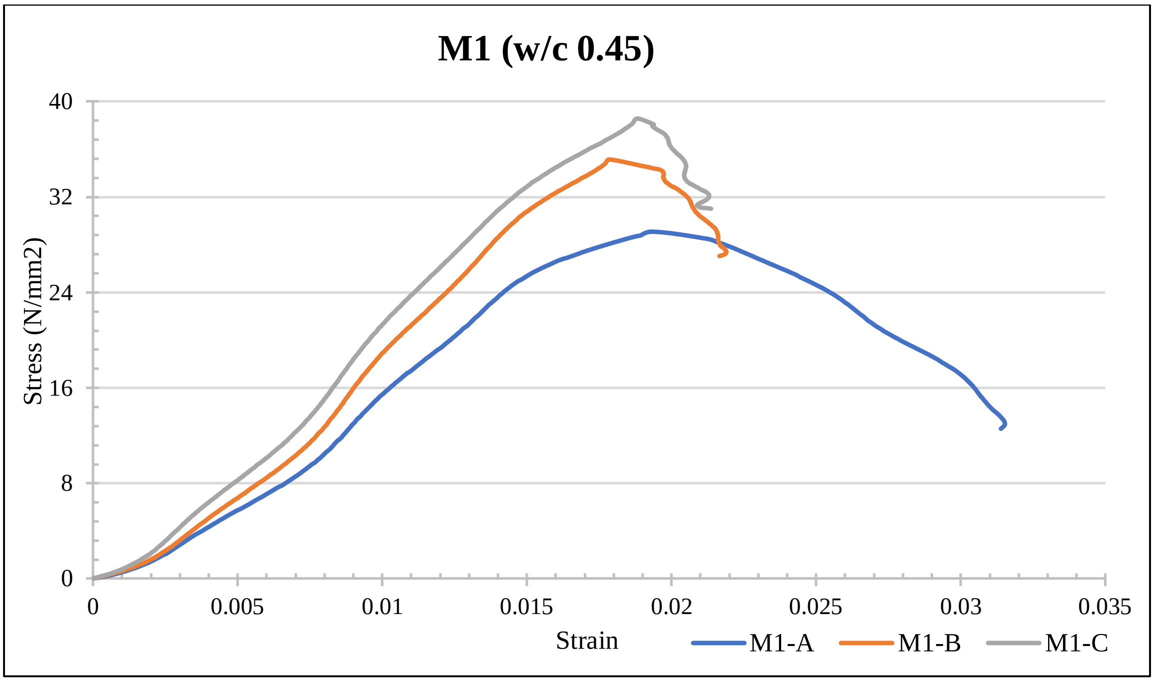

Fig 6.6 Stress-strain behavior of mix M1 for w/c ratio 0.45

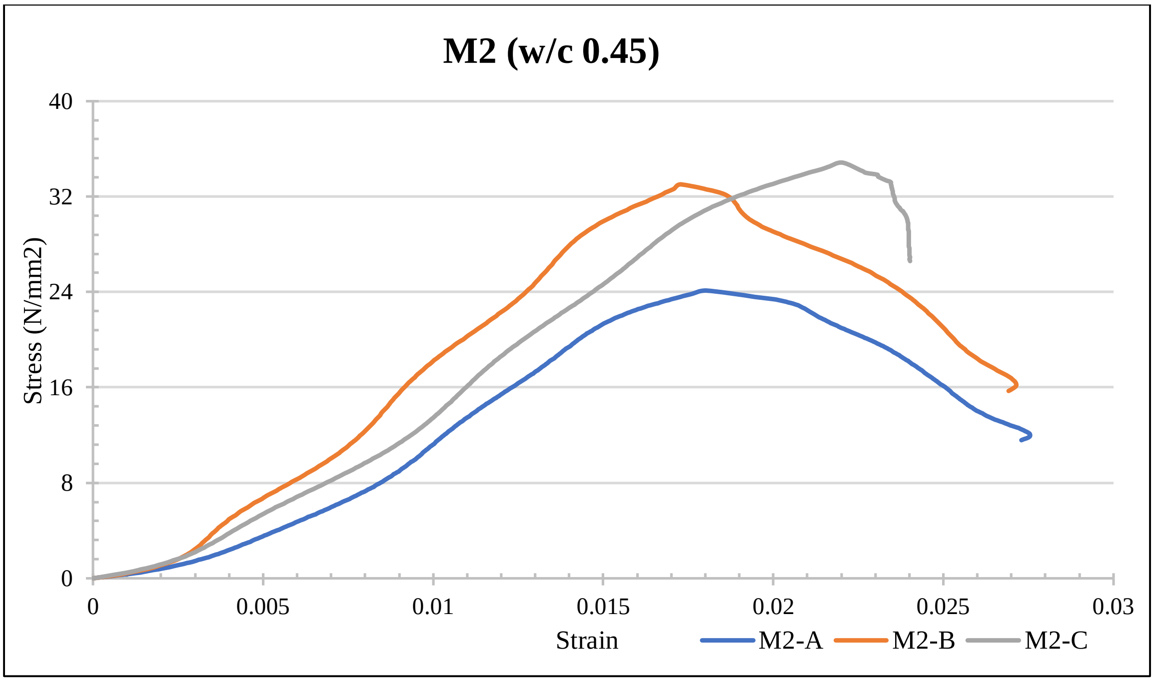

Fig. 6.7 Stress-strain behavior of mix M2 for w/c ratio 0.45

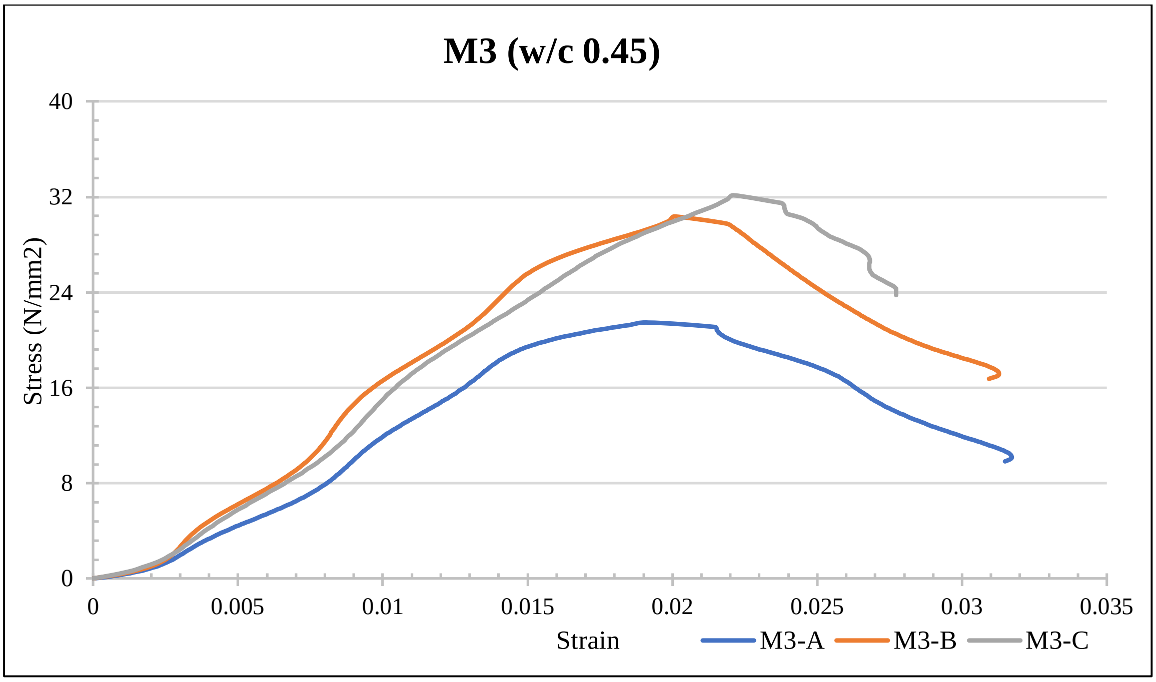

Fig. 6.8 Stress-strain behavior of mix M3 for w/c ratio 0.45

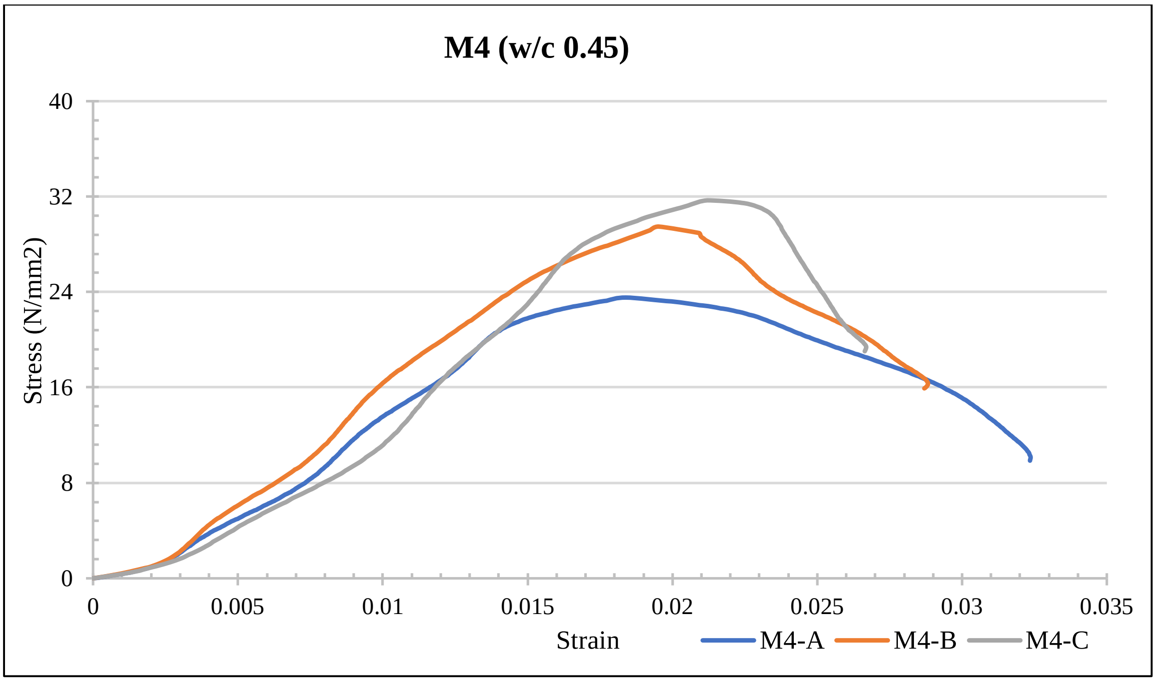

Fig. 6.9 Stress-strain behavior of mix M4 for w/c ratio 0.45

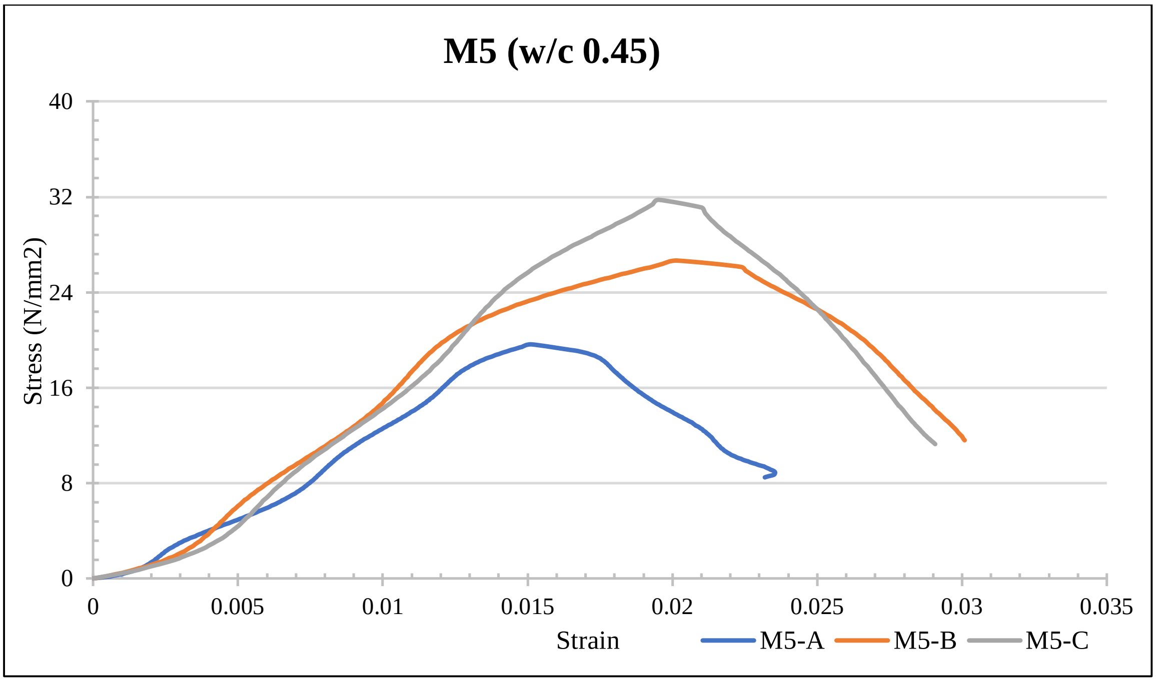

Fig. 6.10 Stress-strain behavior of mix M5 for w/c ratio 0.45

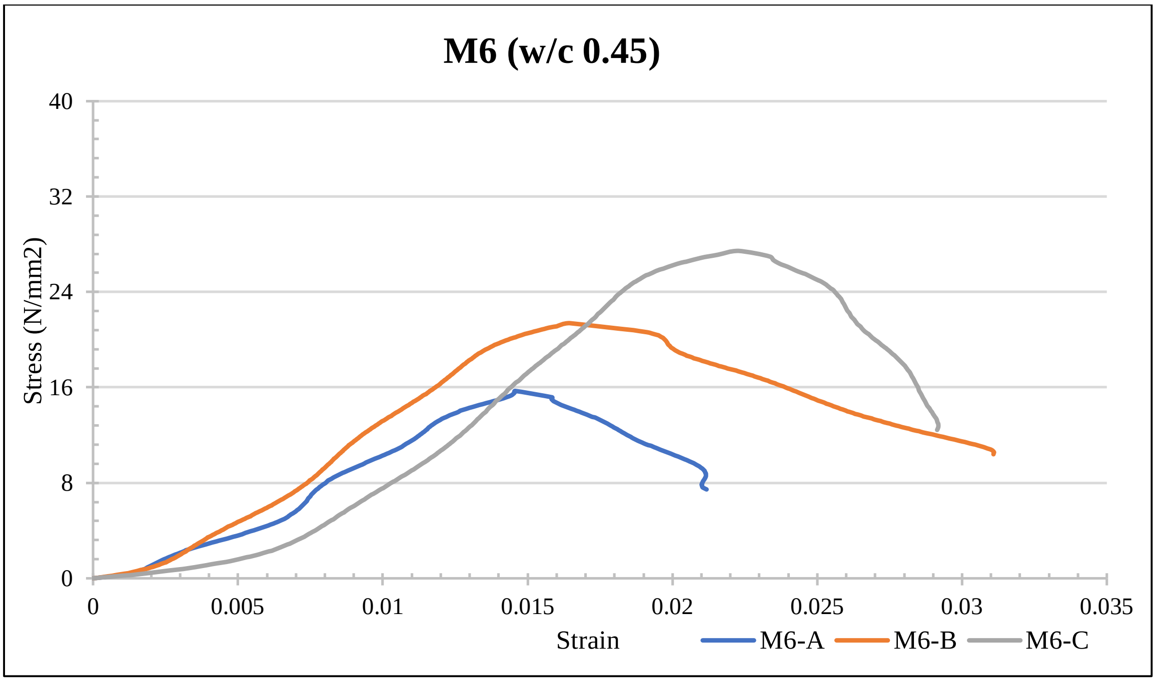

Fig. 6.11 Stress-strain behavior of mix M6 for w/c ratio 0.45

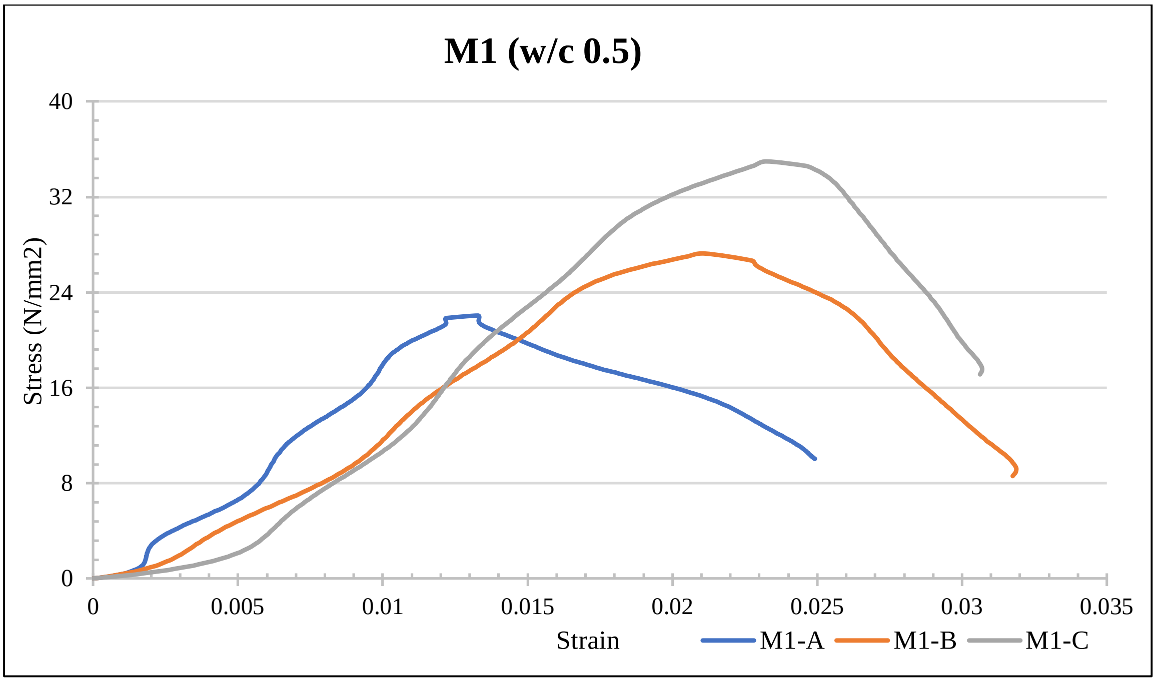

Fig 6.12 Stress-strain behavior of mix M1 for w/c ratio 0.5

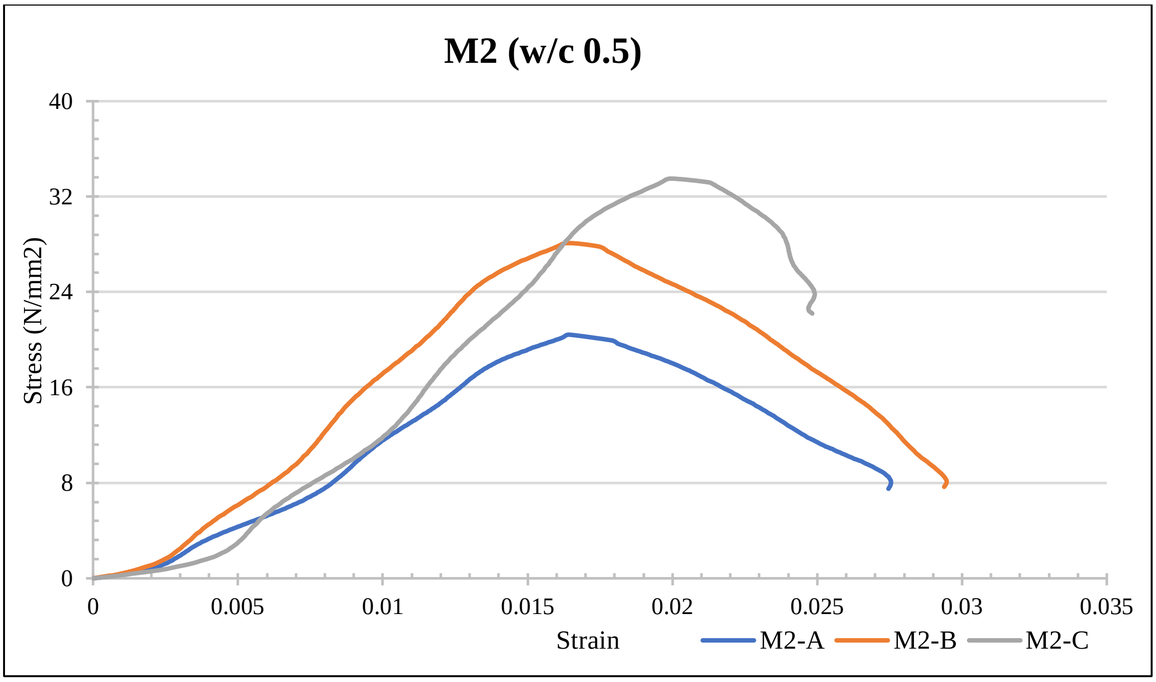

Fig. 6.13 Stress-strain behavior of mix M2 for w/c ratio 0.5

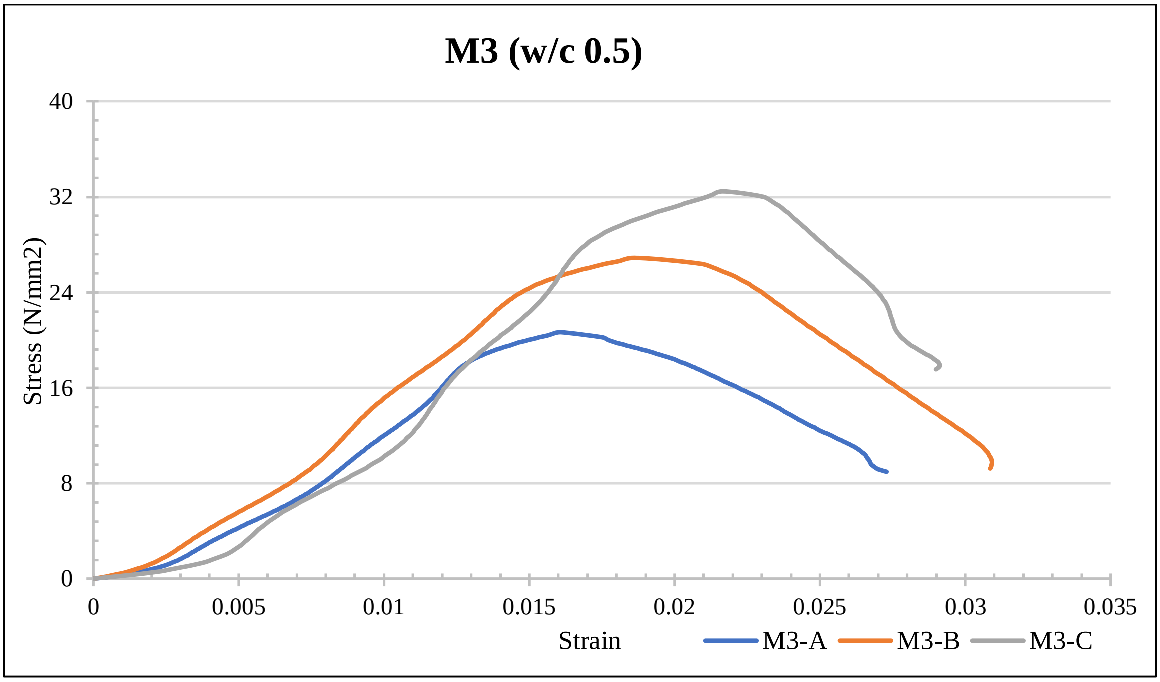

Fig. 6.14 Stress-strain behavior of mix M3 for w/c ratio 0.5

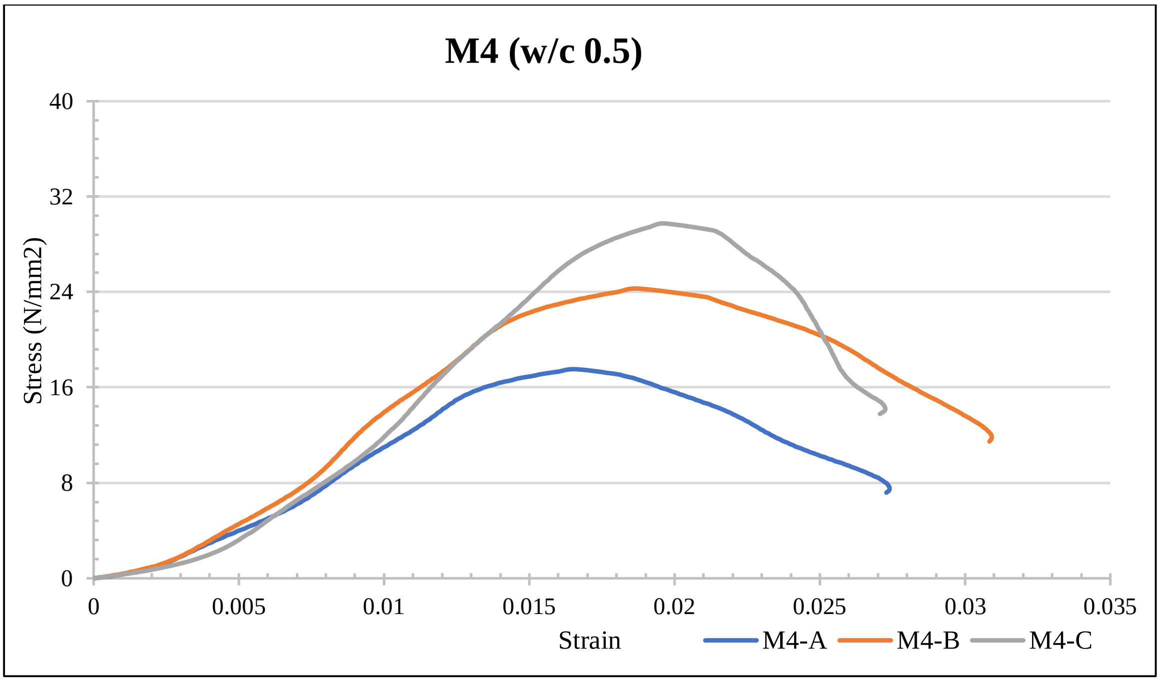

Fig. 6.15 Stress-strain behavior of mix M4 for w/c ratio 0.5

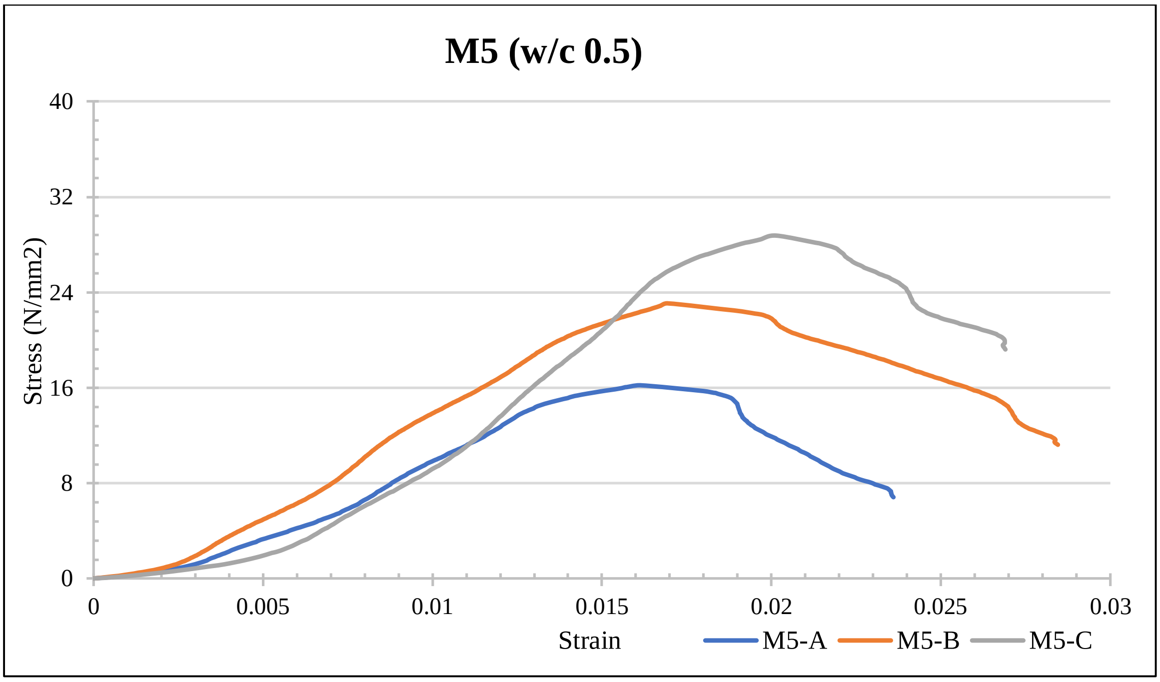

Fig. 6.16 Stress-strain behavior of mix M5 for w/c ratio 0.5

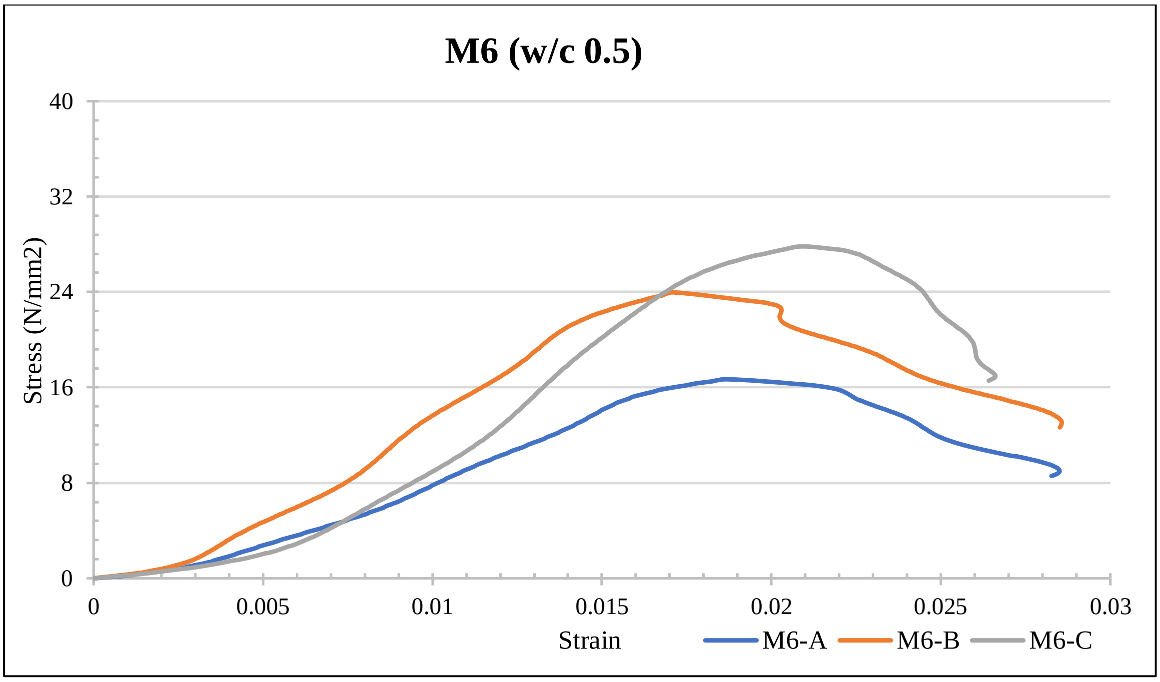

Fig. 6.17 Stress-strain behavior of mix M6 for w/c ratio 0.5

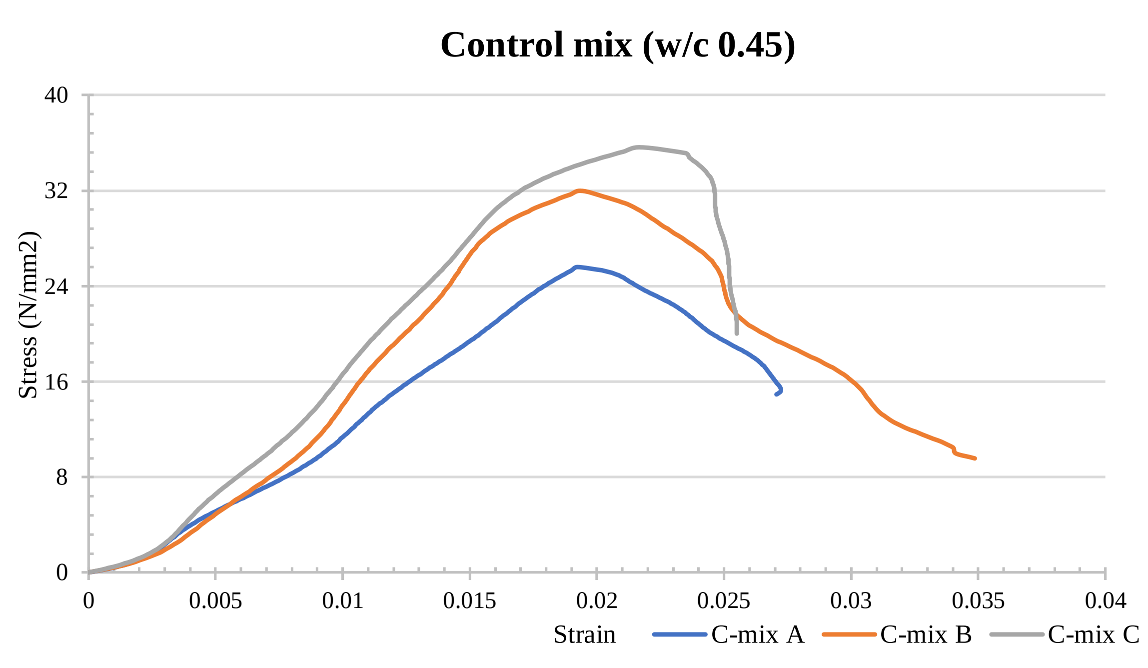

Fig. 6.18 Stress-strain behavior of control mix for w/c ratio 0.45

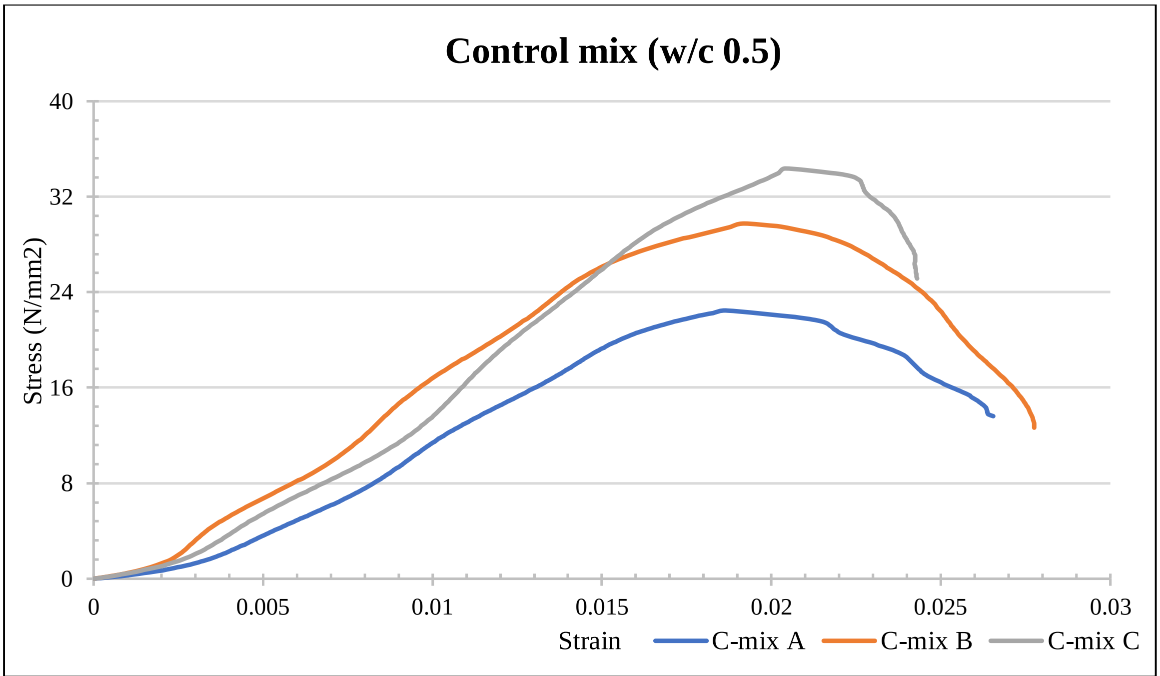

Fig. 6.19 Stress-strain behavior of control mix for w/c ratio 0.5

Along with the relationship between stress and stress curve, a secant modulus is also calculated to remove disparity in the results. The values presented in Table 6.3 show the secant modulus of all the mix proportions with regards to durability. It is calculated at ultimate load and shows, stiffness of the material in the inelastic part of the stress-strain curve. The results coincide very well with the trends as observed in the results of compressive strength test in Fig. 6.20, Fig. 6.21 and Fig. 6.22.

Table 6.3 Secant modulus for all mix proportions after 7-days and 28-days and 56-days

W/c ratio	Mix type	Secant Modulus (in N/mm^2)		
		7 -days	28- days	56-days
0.45	M-1	1501.67	1966.24	2049.77
	M-2	1338.51	1910.24	1581.12
	M-3	1121.05	1513.17	1453.57
	M-4	1280.18	1509.88	1494.88
	M-5	1299.45	1325.16	1627.44
	M-6	1078.04	1299.60	1231.66
	C-Mix	1330.52	1651.28	1640.84
0.5	M-1	1661.36	1290.58	1504.43
	M-2	1242.87	1721.35	1682.50
	M-3	1284.45	1441.07	1499.10
	M-4	1061.50	1296.52	1515.94
	M-5	1004.48	1362.62	1427.82
	M-6	889.63	1399.02	1329.91
	C-Mix	1203.15	1550.96	1684.65

The compressive strength of all the modified concrete mixes, with various percentage of FA and CT in place of cement, for 7-days, 28-days, and 56-days are presented in Fig. 6.20, Fig. 6.21 and Fig. 6.22. These results are compared with the strength of control mixes of respective w/c ratios. 7-days compressive strengths (Fig. 20) of all the mix proportions have been found less than the target strength (i.e., 30 MPa). Compressive strength for mix M1 at 0.45 w/c ratio is the highest among the others mix samples and reduced gradually for the other mix design samples, except control mix (C-Mix), which is slightly lower than M1. The 28-days compressive strength results (Fig. 21) indicate nearly similar trends as of 7-days, but the strength of M1, M2, M3, and M4 at 0.45 w/c ratio are higher than the target strength.

It is to be noted that 28-days strength of all the mix design samples is below 28-days target strength at 0.5 w/c ratio except control mix (C-Mix) which closely approaches the target strength as shown in Fig. 6.21. On the other hand, the results of the 56-days unconfined compression test are very encouraging and demonstrate the positive effect of combined utilization of copper tailings and fly ash to partially replace cement in concrete. In 56-days

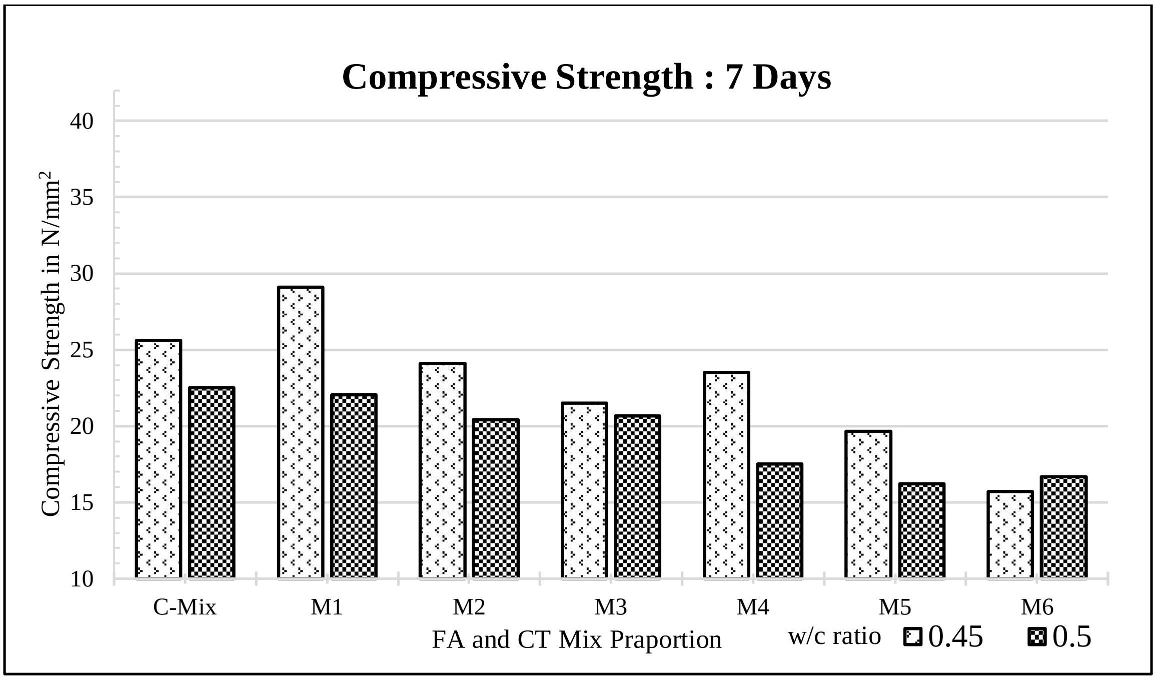

Fig. 6.20 7- s compressive strength test results of modified concrete mix proportions

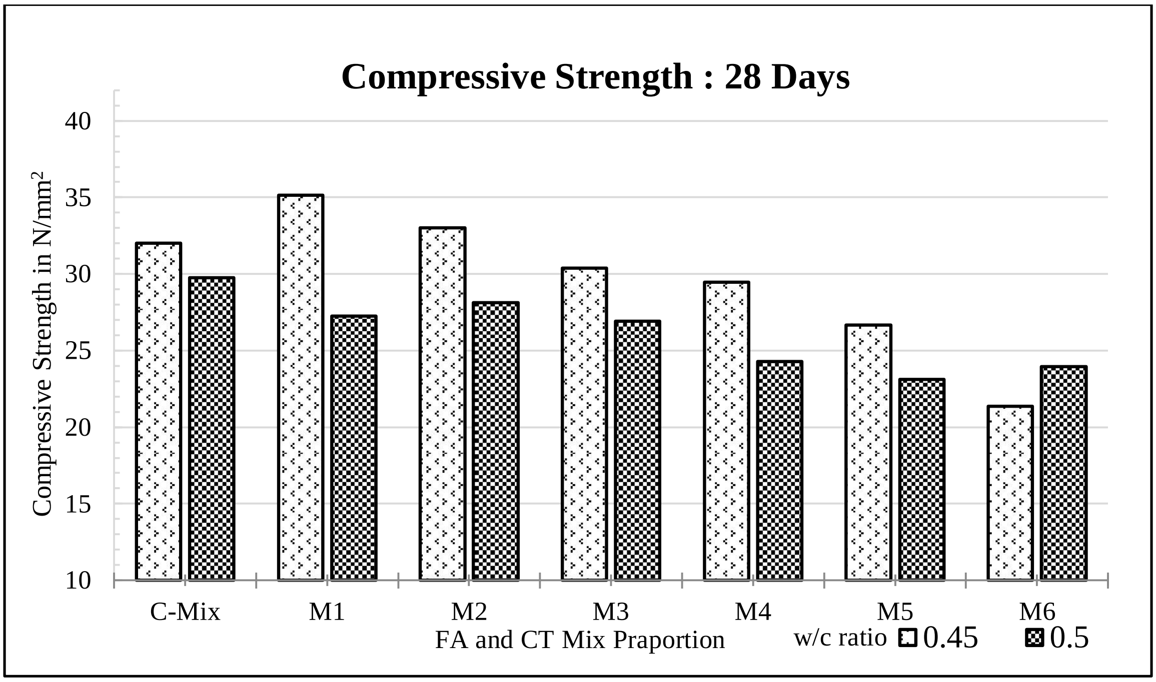

Fig. 6.21 28- days compressive strength test results of modified concrete mix proportions

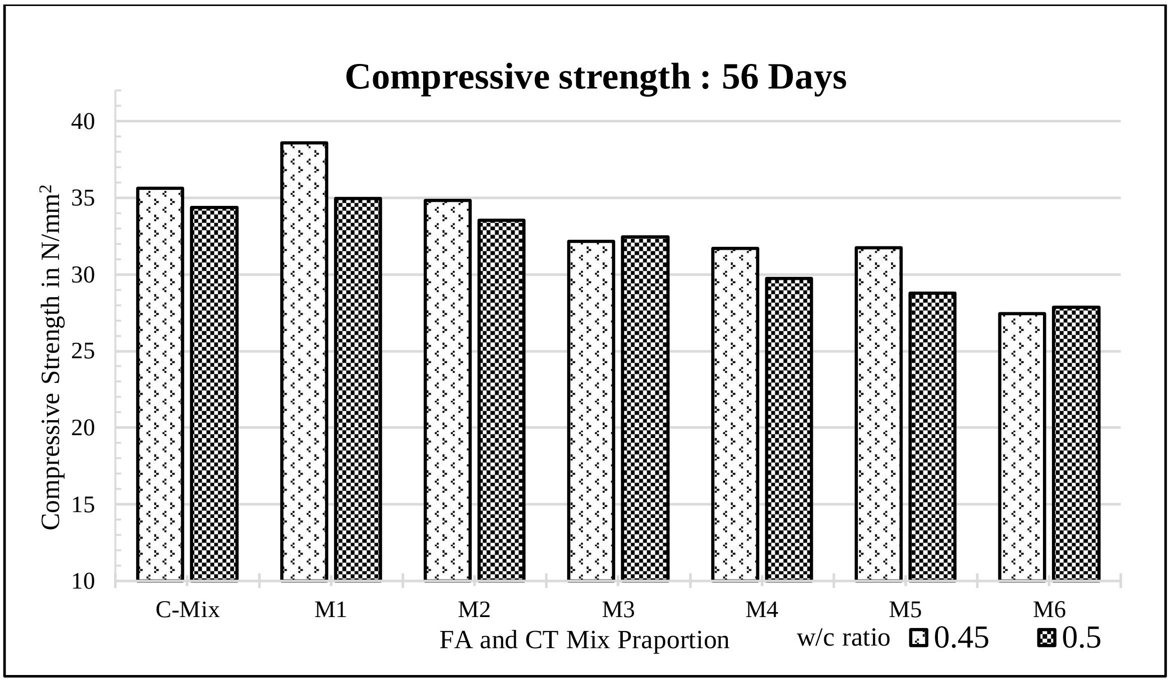

Fig. 6.22 56- days compressive strength test results of modified concrete mix proportions

results (Fig. 6.22), the compressive strength of all specimens with w/c ratio of 0.45 is higher than the target strength except for M6. For 0.5 w/c ratio, the compressive strength of M1, M2, and M3 are significantly higher than the target strength, and for M4 the compressive strength nearly approached to the target strength. The 56-days strength of M5 and M6 at w/c 0.5 are little below the target strength, i.e., 28.7 MPa and 27.85 MPa. Variation in the 56-days ultimate compressive strength results with the control mix is presented in Fig. 6.23, and Fig. 6.24 in the form of a bar chart. The compressive strength of mix M1 has been found about 8.27% and 1.75% higher than the control mix at 0.45 and 0.5 water-cement ratios, respectively. Although the compressive strength of mix M2 and mix M3 is relatively lower than the control mix but higher than the target compressive strength (30 MPa) for both the water-cement ratio. The mix M4 and mix M5 for w/c ratio of 0.45 have compressive strength lower than the control mix (11.09% and 10.89% respectively) but slightly higher (31.68 MPa and 31.75 MPa respectively) than the target strength. The compressive strength of mix M6 is significantly lower for both the w/c ratios 0.45 and 0.5.

From the strength test results, it can be said that the replacement of cement with FA beyond 20% combined with CT of 10%, put an adverse effect on the compressive strength of concrete. It may be since the replaced pozzolanic FA and CT have optimally utilized all the extra lime

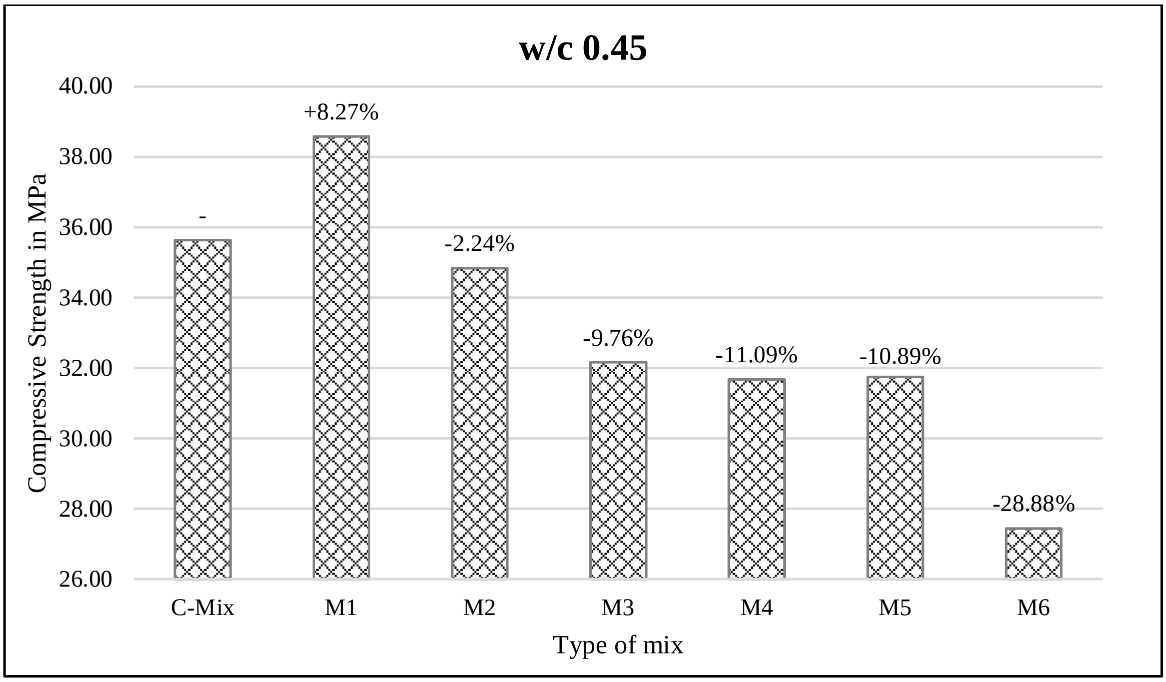

Fig 6.23 Variation in 56-days compressive strength with control mix for w/c ratio 0.45

released during the hydration process. Afterwards the lime would not be available to react with additional pozzolanic material beyond high limits of replacement, leading to a reduction in compressive strength of concrete.

The conformity of the compressive strength results has been verified by standard deviations (detailed in Table A4 of the appendix) of compressive strength results. These results are very less dispersive and exhibit standard deviation of 0.18 N/mm^2 to 1.4 N/mm^2 for 7-days compressive strength, 0.19 N/mm^2 to 1.27 N/mm^2 for 28-days compressive strength and 0.12 N/mm^2 to 2.22 N/mm^2 for 56-days compressive strength.

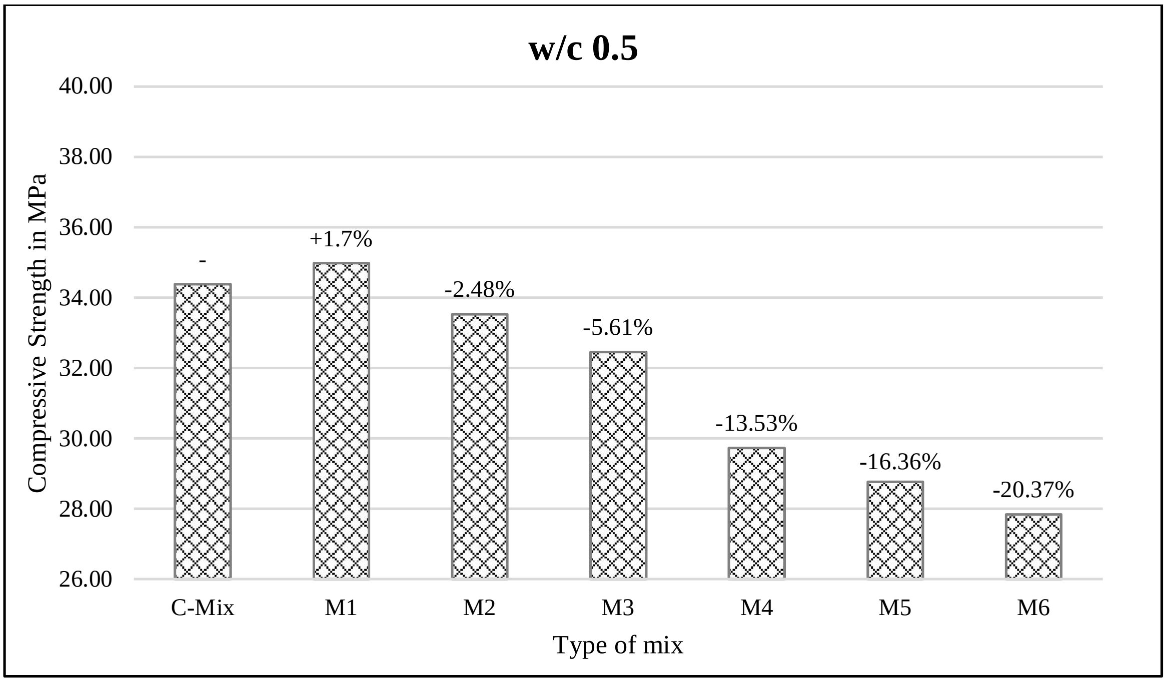

Fig 6.24 Variation in 56-days compressive strength with control mix for w/c ratio 0.5

Table 6.4 Standard deviation of the compressive strength results

w/c ratio	Mix type	Standard deviation 7 -days	28- days	56-days
0.45	M-1	0.34	1.28	1.62
	M-2	0.59	0.19	0.85
	M-3	0.34	0.55	0.50
	M-4	0.54	0.43	0.49
	M-5	0.30	0.53	1.18
	M-6	1.41	1.06	2.23
	C-Mix	0.87	1.27	0.81
0.5	M-1	0.55	1.28	2.18
	M-2	0.68	0.46	1.74
	M-3	0.48	0.53	0.12
	M-4	0.28	1.09	0.90
	M-5	0.32	0.41	0.76
	M-6	1.22	0.70	0.91
	C-Mix	0.18	0.57	1.47