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Research Article

Chemical resistance of hardened mortar containing andesite and marble industry waste powder

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ABSTRACT

The sludge generated during forming processes of marble and andesite rocks is kept in dust form after drying. Due to the high consumption of andesite and marble, the storage and health problems of these dusts arise. Therefore, reducing the environmental impacts of waste and recovering them for the economy is an important issue. For this purpose, in this work, mortar specimens were manufactured using 0%, 5%, 10%, 15% and 20% of waste marble and andesite powders separately by Portland cement. Strength properties of the samples were investigated before and after immersion to the hydrochloric acid (HCl), sodium sulfate (Na_2SO_4) and magnesium sulfate ($MgSO_4$) solutions. The results indicated that partial substitution of Portland cement by andesite and marble powder up to 10% have positive influence on the mechanical properties of the mortars at ambient conditions. In addition, the andesite incorporated mortars have the better performance under the acid and sulfate environments than the other mortars. On the other hand, substitution of Portland cement by marble powder more than 5% has negative influence on the chemical resistance of the mortars.

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1. Introduction

Greenhouse gases along with the natural resources issue are important role on the sustainable development of construction industry. Construction industry is researching for the utilization of substitute alternatives for cement manufacture. In the last decades, there are studies focused on substitution of cement with several wastes such as fly ash, blast furnace slag, rice husk ash, and etc. (Rana et al. 2015; Naik 2008). The CO_2 emission originated from the cement manufacture may also be limited by restricting it with such wastes (Yang et al. 2015; Rana et al. 2015).

Approximately, 7 million tons of natural rock is processed in Turkey for each year, 75% of which is formed at five thousand quarries. Andesite is a type and subtype volcanic and magmatic rock, respectively. Andesite is employed for several architectural and civil engineering applications in Turkey as well as in other countries (Sariisik et al. 2011; Davraz et al. 2018). Powder and sand are disposed as by products during polishing and cutting processes of rocks for several aims. A large-scale andesite manufacture generates vast amount of waste powder; nearly one quarter of the andesite and marble is discharged during polishing, cutting, mining and other applications. Discharge of andesite and marble processing waste powder into the environment can lead to significant health and environmental problems (Soğancıoğlu et al. 2013; Davraz et al. 2018; Ashish 2019; Sarkar et al. 2006). Recovery of waste natural stones in exchange for cement raw materials may cause to significant energy savings processes required for the manufacturing of the final product (Ismail and Ramli 2013; Rana et al. 2015).

The utilization of pozzolans and several admixtures in cementitious composites is a common option for many years (Kara and Arslan 2020). They are employed in concretes, mortars, cements, in the production of structural elements, and combined with other materials such as Portland cement, sand, and lime. Additionally, some al-

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ternative sources may have pozzolanic reactivity. Effects of these materials as pozzolanic materials and for improvement of mechanical performance are depending on their pozzolanic activity. The activity can be identified as the reaction performance of SiO_2 available in the potential material reacting with $Ca(OH)_2$, resulting in secondary C-S-H gels. Andesite powder is a SiO_2-rich waste, and so it may have pozzolanic activity. Despite all the work about the application fields and natural abundance of andesite, its use as natural pozzolan and its pozzolanic activity in mortar or concrete are not well established. (Hamidi et al. 2013; Davraz et al. 2018)

Sulfate attack is one of the most detrimental effects on the endurance of building materials. After the sulfate exposure, expansion, cracking, and spalling are observed on the cement-based materials (Chindaprasirt et al. 2007; Collepardi 2003; Sancak and Özkan 2015) Sulfate attack occurs in cement-based materials when the materials are in touch with a source of sulfate ions, which can be rainwater, soil or groundwater. Sulfate attack manifests itself by spalling and cracking of concrete caused by dilatation and decrease in mechanical performance. The durability of cement-based materials to sulfate effect is influenced by various factors, such as water absorption and permeability. (Shanahan and Zayed 2007; Sancak and Özkan 2015).

Durability to acid attack is an important environmental effect for building materials employed in structural components. Acid attack is generally originated from several industrial processes and other related applications (Selim et al. 2020). It has been stated that hydrated and unhydrated cement phases are decomposed after subjecting to acid attack. Besides, the damage of attack depends primarily on concentration of acid as well as duration of the attack. Acid effect mechanism includes generally pore expanding bringing about porosity and hence a decline in strength of the exposed building material (Selim et al. 2020; Chi and Stegeman 2000; Beddoe and Dorner 2005; Çelikten 2021).

There are many studies performed regarding substituting marble dusts for cement in cement-based composites. (Yamanel et al. 2019; Ashish 2019; Rana et al. 2015; Selim et al. 2020; Singh et al. 2017; Rashwan et al. 2020; Ghorbani et al. 2020; Khodabakhshian et al. 2018; Zhang et al. 2020, Khyaliya et al. 2017; Ergün 2011). There is a variation in the durability and mechanical performance towards the marble dust incorporation. Literature review has identified a few previous studies on the use of andesite powder in mortar/concrete manufacture (Hamidi et al. 2013; Davraz et al. 2018; Sariisik et al. 2011). Pozzolanic effect of mortar containing andesite powder is reported but the literature on this issue is generally quite limited. Besides, the evaluation of the durability properties of the andesite powder incorporated cementitious composites and comparison of their performance with the plain composites is important.

Acid and sulfate attack on marble powder-based mortars or other cement-based composites has previously been evaluated using mixes modified with waste marble powder. In order to encourage the recovery of waste andesite, this research aimed to determine and compare the resistance of globally studied marble powder-modified mixes with waste andesite-modified mixes under the effect of chemical attacks of acid (HCl) and sulfate ($MgSO_4$ and Na_2SO_4) solutions. Use of waste natural stones powder in place of cement are carried out in literature. But the usage of andesite powder as substitution material in cementitious composites did not take enough attention; therefore, more study on the issue may attract recycling andesite powder in the cementitious composites which could also help for protection of natural resources. In this study, the blended cements manufactured by using the waste andesite and marble powder were subjected to acid and sulphate solution and the mortars chemical resistance were investigated. Compressive strength, flexural strength, hydrochloric acid resistance, sodium sulfate and magnesium sulfate resistance of cement mortar containing andesite and marble powder were investigated.

2. Materials

2.1. Cement

Ordinary Portland cement produced by Eskişehir Cement Factory of grade CEM I 42.5 R in compliance with TS EN 197-1 (2012) was used in the mortars. The density of the cement was 3.13 g/cm^3. X-ray fluorescence results of cement is given in Table 1.

2.2. Andesite and marble powder

Waste andesite powder (AP) and waste marble powder (MP) were employed in the mortar mixtures. The powders were taken from a quarry in Afyon city of Turkey. The density of AP and MP were 2.68 and 2.34 g/cm3, respectively. Before using AP and MP in mortar mixtures, they were sieved from 125 μm sieve and dried at 105°C. The chemical oxide compositions of AP and MP are given in Table 1. Sieve analysis of AP and MP are presented in Table 2.

2.3. Sand

Standard sand (Rilem Cembureau) defined in TS EN 196-1 (TS EN 196-1 2009) was employed for mortar mortar manufacture. The water absorption rate and dry specific gravity of the sand were 0.57% and 2.63, respectively. Sieve analysis of standard sand is given in Table 3.

Table 1. Chemical oxide compositions of cement, andesite and marble powder.

Oxide Content, %	CaO	SiO_2	Al_2O_3	Fe_2O_3	SO_3	K_2O	Na_2O	MgO	LOI
Cement (PC)	62.87	19.91	5.31	3.23	3.27	0.64	0.29	1.88	2.6
Andesite Powder (AP)	6.32	57.82	19.24	5.87	0.22	2.88	3.14	1.87	1.8
Marble Powder (MP)	58.41	4.57	0.59	0.24	0.17	1.1	0.27	4.56	30.0

Table 2. Sieve analysis of andesite and marble powder.

Sieve size, mm	0.125-0.090	0.090-0.062	0.062-0.012	0.012-0
AP, %	12	29	54	5
MP, %	8	24	61	7

Table 3. Sieve analysis of sand.

Sieve size, mm	2.00	1.60	1.00	0.50	0.16	0.08
Remaining on Sieve, %	0.0	3.2	32.6	68.8	87.2	99.6

3. Methodology

The andesite powder (AP) and marble powder (MP) were utilized in the mortar mixtures as substitution material by the Portland Cement (PC). In preparation of binder paste, AP and MP were employed as a substitution material of cement in 0%, 5%, 10%, 15% and 20% proportion by mass. The proportion of water (W) to total binder content (W/AP+PC) or (W/MP+PC) ratio was 0.5 and sand to total cementitious material proportion of content was 3. The amounts of materials used for the production of mortar mixtures for three-cell mortar mold (4x4x16 cm) are illustrated in Table 4. As seen on the table, the mortar mixes were coded as the substitution of cement respectively. Moreover, the mixing process of the mortars included the following steps. Water and powder binder were poured to the case of Hobart mixer and run at low running rate of 140 rpm for 30 sec. After that, the sand was poured in the bowl in 30 sec. Then, the mixture was mixed at high running rate 30 sec. After high running rate, the mixture was kept waiting at stopped condition for 90 sec. Then, the mixture was mixed at high running rate of 280 rpm for 60 sec. Finally, the mixture was casted into 4×4×16 cm molds after waiting 15 sec. according the TS EN 196-1. After that, the mixes were kept at standard curing conditions until the day of testing. After curing process, mortar specimens with the dimensions of 4×4×16 cm were extracted from the molds to employ the several tests. Three specimens were used for each test and the final results calculated from averaging of results of three specimens.

Firstly, the unit weight values of the mortars were determined in saturated dry surface conditions. Flexural strength (FS) test was conducted on complying with TS EN 1015-11 (TS EN 1015-11:2000) standard, using three-point loading assembly on prismatic specimens with 100 mm span distance between supports. After the FS test, two samples of broken prisms were used to measure the compressive strength (CS) (4×4 cm), complying with TS EN 1015-11. Average of three prismatic samples results were taken as FS value, and average of six samples was taken as CS value. In addition, 6 specimens for each mix were exposed to 5% $MgSO_4$, 5% Na_2SO_4 and HCl (pH=2) solutions for 90 and 180 days, separately. The FS and CS tests were done on these specimens before and after exposure to the solutions. 56 days aged specimens were used for the FS and CS tests before the immersion to determine the pozzolanic effects of the AP and MP.

Table 4. Amounts of materials used in the mortars (g).

Mix	PC	MP	AP	Water	Sand
PC	450.0	-	-	225	1350
MP5	427.5	22.5	-	225	1350
MP10	405.0	45.0	-	225	1350
MP15	382.5	67.5	-	225	1350
MP20	360.0	90.0	-	225	1350
AP5	427.5	-	22.5	225	1350
AP10	405.0	-	45.0	225	1350
AP15	382.5	-	67.5	225	1350
AP20	360.0	-	90.0	225	1350

4. Results and Discussion

4.1. Unit weight

Unit weights of mortars are illustrated in Table 5. The average unit weight value of PC mortars was 2.09. The unit weights of AP and MP incorporated mortars were ranged between 2.13 g/cm^3 and 2.21 g/cm^3 and between 2.11 g/cm^3 and 2.18 g/cm^3 before immersion to acid or sulfate solutions, respectively. The results show that the hardened average unit weights of AP and MP incorporated mortars were up to 3% and 4% higher than the unit weights of PC mortars before immersion to solutions, respectively. The average unit weight of the MP incorporated mortars increased to about 2% and 3% after immersion of the HCl solution for 90 and 180 days, respectively. Due to the difference in the concentration of the HCl, Na_2SO_4 and $MgSO_4$ solutions and the water in the mortar, the unit weights of the mortars were increased up to 4.2%, 6.1% and 7% after immersion of the solutions, respectively. The increase in the unit weights of the mortars with the solution immersion was compatible with the density of the acid or sulfate solutions.

4.2. Flexural strength

The final flexural strength (FS) results in the mortars are plotted in Figs. 1, 2 and 3. From the results, it could be observed that both powder type and substitution level of cement had important impacts on the final FS development of the mortars. The FS values of mortar specimens after acid solution exposure were compared relative to the FS values of unexposed specimens. The FS values of AP and MP incorporated mortars after exposure to 90 and 180 days HCl (pH=2%) solutions are illustrated in Fig 1. After the subjection of HCl solutions for 90 and 180 days, the MP incorporated mortars exhibited the lowest FS values. After the immersion HCl solution for 90 and 180 days the FS values of MP15 mortars were decreased to almost 4.8% and 17.9%, respectively. Minimum FS reductions in all the mortars were determined for AP15 coded mortars. After the immersion for 90 and 180 days, the FS values of AP15 mortars were decreased to almost 0.3% and 6.1%, respectively. It's concluded that the AP containing mortars performed better against HCl acid attack than the other mortars.

Table 5. Unit weight values of the mortars (g/cm^3).

Mortar mixtures	Before immersion	HCl 90d	HCl 180d	Na_2SO_4 90d	Na_2SO_4 180d	$MgSO_4$ 90d	$MgSO_4$ 180d
PC	2.09	2.16	2.13	2.18	2.21	2.17	2.19
MP5	2.11	2.21	2.19	2.14	2.16	2.21	2.22
MP10	2.15	2.21	2.18	2.18	2.19	2.18	2.17
MP15	2.17	2.24	2.22	2.24	2.25	2.20	2.21
MP20	2.18	2.19	2.20	2.25	2.27	2.24	2.25
AP5	2.13	2.23	2.22	2.24	2.26	2.27	2.28
AP10	2.19	2.26	2.21	2.28	2.30	2.28	2.29
AP15	2.17	2.24	2.20	2.25	2.26	2.28	2.31
AP20	2.21	2.23	2.23	2.33	2.32	2.31	2.31

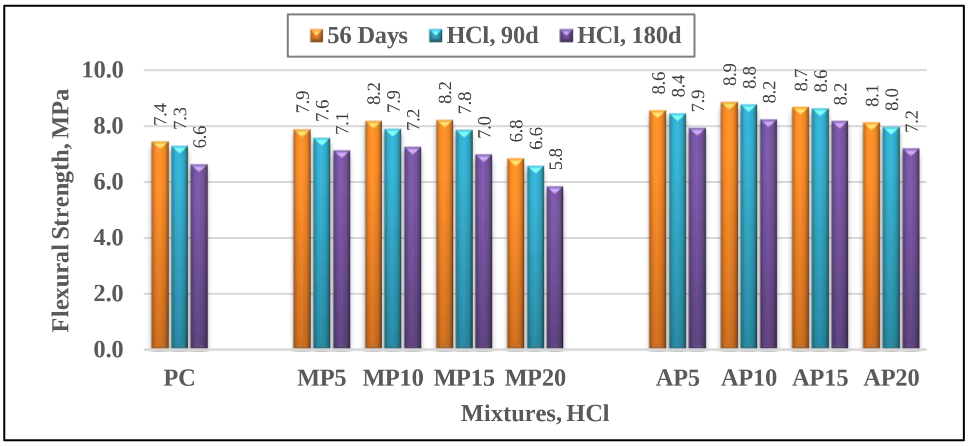

Fig. 1. Flexural strength of mortars exposed to HCl.

The final FS values of AP and MP incorporated mortars mixtures after subjection to 5% Na_2SO_4 solution for 90 days were in the ranges of 6.9-8.2 MPa and 8.1-9.1 MPa, respectively (Fig. 2). The final FS values of AP and MP incorporated mortars after immersion for 180 days were in the ranges of 6.6-8.0 MPa and 8.1-9.0 MPa, respectively. The results indicated that relative to PC mortar mixture, FS increased across all the periods up to 10% AP and MP ratios. FSs of mortars were enhanced with the employment of MP/AP partially in place of cement with respect to PC mortar. When exposure to Na_2SO_4 time increases from 90 days to 180 days, FSs of all the mortars decreased due to degradation of cement paste formation. Maximum FS loss was about 5.8% in MP15 mortars subjected to Na_2SO_4 solution for 180d.

The FS results of the mortars subjected to 5% $MgSO_4$ solution are represented in Fig. 3. The sulfate resistance of the mortars was considered with respect to difference in FS of specimens after immersion to 5% $MgSO_4$ solution for 90 and 180 days, separately. After the immersion for 90 and 180 days, the FS values of PC mortars were decreased to almost 0.5% and 3.0 %, respectively. FS values of MP mortars decreased between 2% and 3.5% after subjecting 5% $MgSO_4$ solution for 90 days. At 180 days' immersion, the strength losses increased and the strength loss of MP-containing mortars was between 4% and 13%. As for the mortars containing andesite, lower strength values compared to PC mortars under the influence of $MgSO_4$ for 90 days were only seen in mortars with code AP20. After immersion of 180 days, FS loss was observed between 1.8% and 5.9% in other mortars except AP15. FS loss was not observed in AP15 coded mortars under the influence of $MgSO_4$ for 90 or 180 days. In general, FS values of AP modified mortars better than MP modified mortars under the 5% $MgSO_4$ attack for 90 and 180 days. The better performance of the AP-incorporated mortars in the acid and sulfate solutions can be attributed to the pozzolanic activity of the AP. The pozzolanic activity of the AP was also reported in a previous work (Hamidi et al. 2013; Davraz et al. 2018).

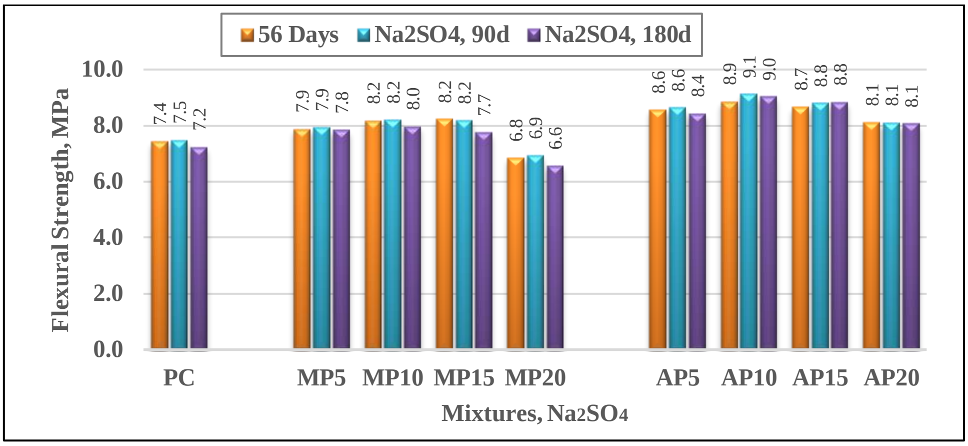

Fig. 2. Flexural strength of mortars exposed to Na_2SO_4.

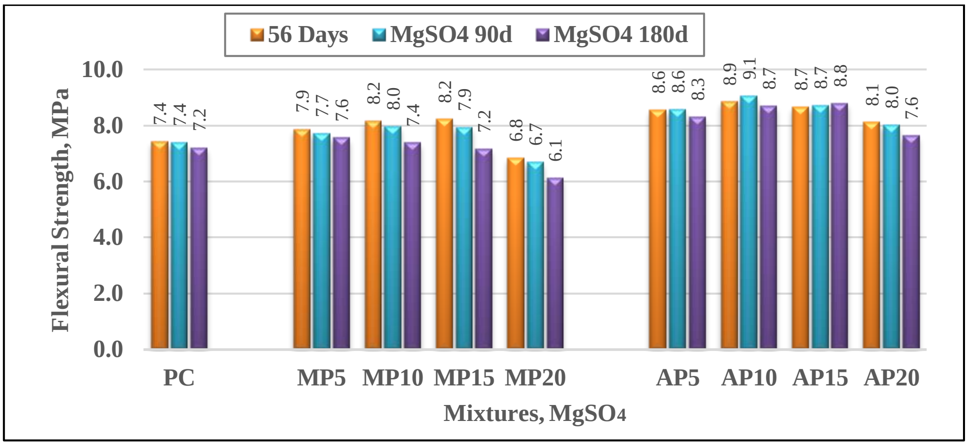

Fig. 3. Flexural strength of mortars exposed to $MgSO_4$.

4.3. Compressive strength

The compressive strength (CS) values of mortars after exposure to HCl, Na_2SO_4 and $MgSO_4$ solutions are presented in Figs. 4, 5 and 6, respectively. The highest CS values was obtained from the AP10-coded mortars before exposure to the solutions. Besides, except for the MP20, the CSs of all the AP or MP incorporated mortars had higher CS than the PC mortar. The positive effect of AP (Hamidi et al. 2013; Davraz et al. 2018) and MP (Yamanel et al. 2019; Ashish 2019) on the CS of the Portland cement-based mortars was also reported in previous works. The acid durability of the mortars was determined with respect to change in CS of mortar samples after immersion to HCl solution for 90 and 180 days, separately. Fig. 4 illustrates the initial and final CS results of the mortars after exposure to the HCl solution. The CS results of PC mortars after 90- and 180-days immersion in 5% HCl acid solution were 46.4 and 40.3 MPa, respectively. Initial CS value of PC mortar was 49.3 before immersion to solution. The highest CS values were observed on the MP incorporated mortars for MP5 as 48.6-45.0 MPa and on the AP modified mortars for AP10 as 58.9-52.2 MPa after subjection for 90 and 180 days', respectively. Minimum CS loss was about 10.6% in AP5 mortars after exposure to HCl-180d. Selim et al. (2020) studied the sulfuric and acetic acid resistances of marble dust incorporated Portland cement pastes. Their results showed that 5% replacement of MP by cement improved the acid resistance of pastes. However, replacement of marble dust by Portland cement at high levels of 15% and 20% decreased the acid resistance of pastes, significantly. These findings are compatible with this present work. The worse acid resistance of MP15 and MP20 mortars with respect to the PC and MP5 mortars can be attributed to the filler effect of MP and its low pozzolanic activity.

The residual CS of the mortars after immersion to 5% Na_2SO_4 solution are shown in the Fig. 5. The final CS values of MP and AP mortars were in the ranges of 46.4-57 MPa and 56.1-69.4 after subjection to Na_2SO_4 solution for 90 days. After exposure for 180 days, average values of the MP and AP incorporated mortars were decreased between 9.1 MPa and 5.8 MPa in comparison with the values calculated after 90 days' immersion. The maximum final CS values of 57.0 and 69.4 MPa were observed on the mortar mixtures manufactured as the MP10 and AP10 in all the series for 90 days, respectively. The enhanced durability may be attributed to the decline of $Ca(OH)_2$ (Portlandite) formed as a result of the hydration of cement because of the decrement in cement content by substitution. Therefore, the amount of gypsum occurred from the reaction between sulfates and the Portlandite declined, and consequently the ettringite formation, the reason for volume deterioration and expansion, is controlled (Rashwan et al. 2020). The highest CS value of 61.2 MPa was achieved on the AP10 mortars after subjection to Na_2SO_4 solution for 180 days. Besides, increase in the waste powder ratio had negative influence on the final CS of the mortar mixtures as reported for the results in sulfate environment after %10 ratio. The lowest residual final CS of 39.5 MPa was calculated for the MP20 after subjection to Na_2SO_4 solution for 180 days.

The initial and final CS values of the mortars after subjection in 5% $MgSO_4$ solution for 90 and 180 days are illustrated in the Fig. 6. While the lowest final CS of 36.4 MPa was seen on the MP20 mortars after immersion to the solution for 180 days, the highest CS of 62.9 MPa was obtained on the AP10 mortars at same condition. AP mortars had superior performance under the $MgSO_4$ attack than the PC and MP mortars. Previous studies reported that reducing the content of $Ca(OH)_2$ in Portland-cement-based composites by incorporating various pozzolans can improve the $MgSO_4$ durability of these composites and reduce softening of C-S-H gel and the degree of attack (Zhang et al. 2020). The better durability performance of the AP incorporated mortars indicated that AP had considerable pozzolanic activity in addition to its filler effect.

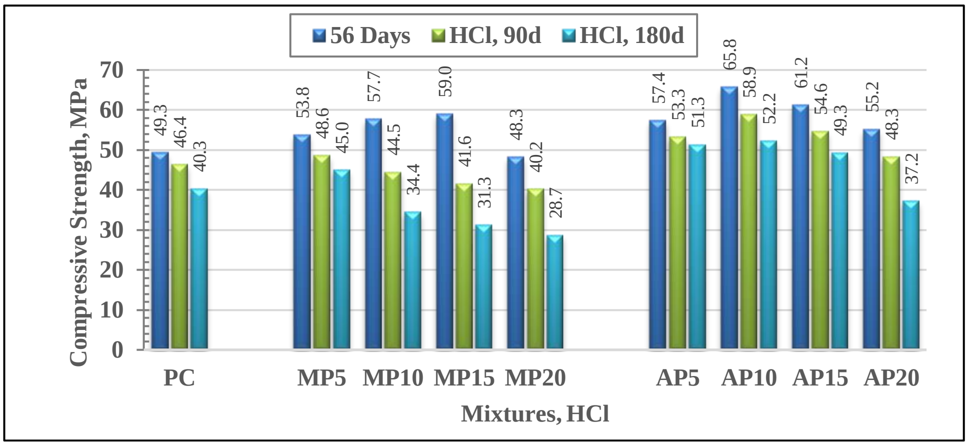

Fig. 4. Compressive strength of mortars exposed to HCl.

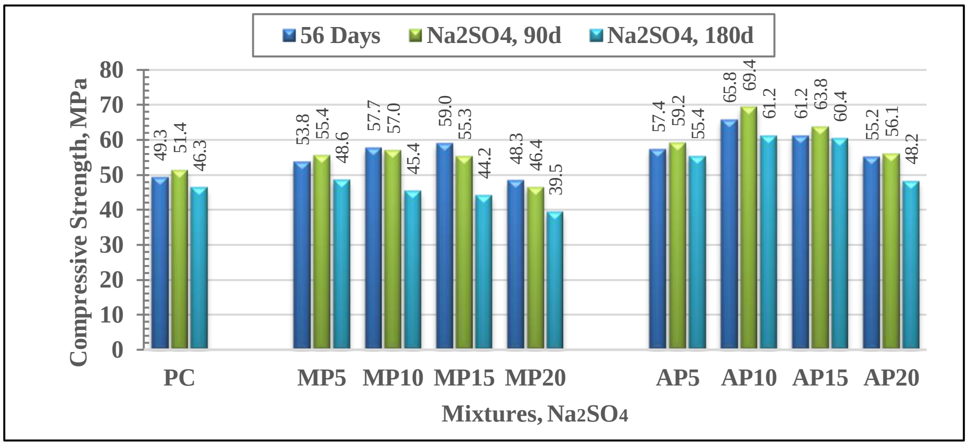

Fig. 5. Compressive strength of mortars exposed to Na_2SO_4.

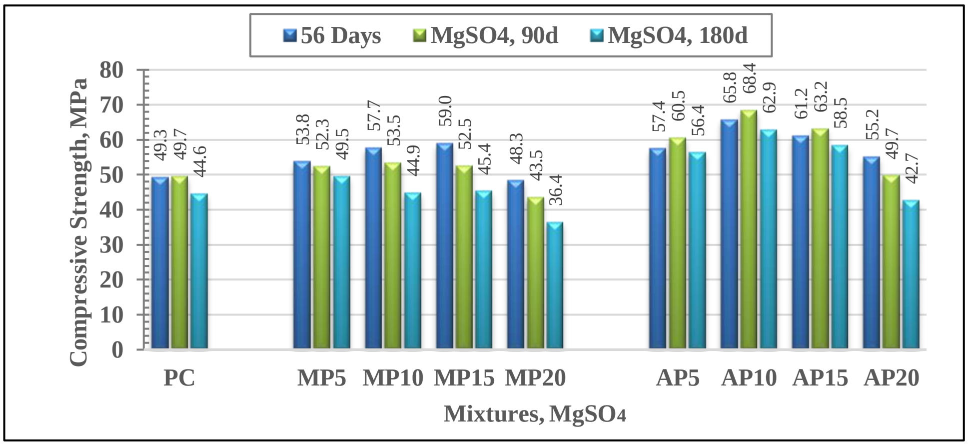

Fig. 6. Compressive strength of mortars exposed to $MgSO_4$.

5. Conclusions

- Utilization of AP and MP as substitution material for cement may contribute to reduce CO_2 emission by reducing cement consumption. Thus, it can help to conserve the environment.
- The most suitable replacement ratios for concretes containing MP and AP exposed to environmental conditions were determined as 5% and 10%, respectively.
- The strength development of mortar was affected by the level of cement replacement with AP. AP content greater than or equal to 10% is beneficial to the compressive strength of mortar, whereas the flexural strength significantly increases up to an AP content of 15% and begins to decrease at an AP content of 20%.
- The substitution of AP with PC up to 10% enhanced the acid and sulfate durability of the mortars, significantly.
- Substitution of MP by PC up to 15% increased the mechanical properties of mortars at ambient conditions. However, incorporation of MP in PC mortars had negative effect on the durability properties of the mortars. These states indicated that MP had only filler effect on the mortars with very low pozzolanic effect.
- HCI solution had more detrimental influence on the mortars than the sulfate solutions. The CS loss of mortars was in the range of 18% and 47% after immersion of 180d in HCI solution. The CS losses of mortars was in the ranges of 3-25% and 2-25% after immersion of 180d in Na_2SO_4 and $MgSO_4$ solutions, respectively.

The utilization of AP up to 20% substitution for cement is recommended for mortar production in respect of waste elimination. Besides, use of AP by cement is recommended in mortars subjected to hazardous environmental impacts.

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Conflict of Interest

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this manuscript.

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Challenge Journal of Concrete Research Letters

Research Article

Use of crushed bricks and recycled concrete as replacement for fine and coarse aggregates for sustainable concrete production

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ABSTRACT

The growing concern over the significant ecological changes requires sustainable developments in all fields. Concrete production is one of the largest consumers of natural resources as it consumes a huge volume of natural fine and coarse aggregates, which constitute 70% - 80% of the concrete volume. It is evident that such large amount of concrete production in the growing construction industry puts significant impact on the use of natural resources and the environment. Hence, investigating the use of recycled materials to replace the finite natural resources became evident and is the focus of researchers. In this research, the use of waste crushed bricks (CB), and crushed recycled concrete (CRC) as a partial replacement of fine and coarse aggregates in concrete was studied. The replacement ratios of 10%, 50%, and 100% by weight of either fine or coarse aggregates were used. Eight concrete mixes with 168 specimens were tested for compressive, splitting tensile as well as, flexural strength. All tests were carried out at ages of 7, 28 and 56 days. The results indicated that there is a feasibility of using bricks and concrete wastes in concrete mix as a partial replacement of course and fine aggregates. It is deduced that a 50% replacement ratio of coarse aggregate with crushed concrete resulted in a 30%, 25%, and 23% increase in compressive, tensile, and flexural strengths, respectively. While 50% replacement ratio of fine aggregate with crushed bricks resulted in a 23%, 28%, and 19% increase in compressive, tensile, and flexural strengths, respectively. The most effective mix was at 50% replacement ratio of coarse aggregate with crushed concrete in combination with 50% replacement ratio of fine aggregate with crushed bricks. The results of this mix showed 32%, 28%, 26% increase in compressive, tensile, and flexural strengths, respectively.

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1. Introduction

Concrete is a composite material composed of aggregates, chemically bound together by hydrated Portland cement. These aggregates strongly influence concrete's freshly mixed and hardened properties, mix proportions, and economy (Sajan et al. 2022; Francesco et al. 2021).

In the last decade, amount of construction waste has considerably increased due to the demolition of old structures (Kirthika et al. 2022). With the growing new construction and re-construction of buildings to improve the living standard, the reserves of natural aggregates depleted rapidly (Mohamed et al. 2021). Hence, social, and environmental pressures have driven the use of recycled wastes to partially replace the natural resources (Maciej et al. 2023). The application of recycled concrete aggregate has sometimes remained limited to low valued purposes such as road base materials due to the unstable supply of the waste to the recycling facilities and the fact that the recycling techniques was not satisfactory to produce a good quality recycled waste (Dang et al. 2020; Kazemian et al. 2019).

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With the improvement of the recycling techniques, the use of recycled materials has become the focus of researchers as a viable replacement of natural resources (Abdulkadir et al. 2020; Zheng et al. 2018).

Many researchers concluded that recycled materials can be used as aggregates in new concrete, which offer a viable route to convert the waste to a valuable resource (Yang 2018; Pan et al. 2020). Shruthi (2018) studied the effect of using crushed brick powder as a partial replacement of sand on the properties of concrete. They concluded that the maximum compressive strength is obtained when 40% of brick powder was replaced with fine aggregate.

The effect of different types of recycled concrete aggregates (RCAs) on the equivalent concrete strength and drying shrinkage properties was analyzed by (Memon et al. 2022). Their conducted test results showed that the concrete with RCAs exhibited compressive strength, modulus of elasticity, and flexural strength values equivalent, within 2% variation, to those values of the companion natural aggregate concrete.

Tiwari et al. **(**2016) studied replacement of recycled coarse aggregates with natural coarse aggregates in concrete by ratios of 0%, 50% and 100%. They found an increase of compressive strength by 27%, and 34% at 50%, and 100% replacement ratios, respectively.

According to the investigation made by Siva et al. (2017) of replacing varying percentage of fine aggregates by crushed spent fire bricks with varying percentage of 10%, 15%, 20% & 25% and optimum percentage of replacements is made and strength and workability parameters are studied. The workability of concrete gets decreased with the addition of the crushed spent bricks, and the maximum strength was gained at 20% replacement ratio compared to conventional concrete.

On the other hand, there are several studies stated reduction in concrete strengths incorporating crushed brick (CB) as a replacement of the natural fine aggregate (NFA) or crushed recycled concrete (CRC) as a replacement of natural coarse aggregate (NCA) (Cuesta et al. 2022; Tamashiro et al. 2022). Even in full scale reinforced concrete elements, when Mahdi et al investigated the effect of using concrete mix with 100% recycled concrete aggregate, they found that ultimate flexural strength decreased with higher deflection corresponding to that of natural aggregates (Mahdi et al. 2023).

The present research focused on the use of CB and CRC as an alternative solution for natural fine and coarse aggregates with the aim of adding to the knowledge in this filed which may lead to a more confidence in using of recycled building materials. The effect of using different percentages CB and CRC as replacement for the fine and coarse aggregate in the concrete mix was experimentally investigated and the optimum percentage of replacement that results in the best possible mechanical properties of produced concrete was proposed.

2. Experimental Program

Th**e** experimental program of the present research consisted of testing **e**ight concrete mixes with different percentages of replacement materials namely: 0% (control mix), 10%, 50%, and 100% for each of CB as fine aggregates and CRC as coarse aggregates. Three mixes containing fine aggregates substitutions, other three mixes containing coarse aggregates substitutions. While the last mix containing both fine and coarse aggregates substitutions by equal percentages of 50%. A total of 168 specimens were cast and tested for compressive, splitting tensile as well as, flexural strengths. All tests were conducted in this study were according to American Standard Specifications for Testing and Materials (ASTM).

2.1. Materials

Different materials were used in the present experimental program; natural fine aggregates (NFA), coarse aggregates, cement, crushed bricks (CB), and crushed recycled concrete (CRC).

2.1.1. Cement

CEM Type I normal Portland cement was used with a specific gravity of 3.15. The cement specifications are according to ASTM C150/2007, and presented in Tables 1 and 2.

Table 1. Chemical composition of cement (OPC-CEM I).

Chemical composition	SIO_2	AL_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	K_2O	TiO_2	P_2O_2	LOI
O.P.C	20.1%	4.9%	2.5%	65%	3.1%	2.3%	0.2%	0.4%	0.21%	< 0.9%	2.4%

Table 2. Physical properties of cement (OPC-CEM I).

Property	Test results	Specification limits
Fineness in terms of specific surface area (cm^2/gm)	3120	> 2500
Initial setting time (min.)	100	> 45
Final setting time (hrs.)	5.0	< 10

2.1.2. Natural fine aggregates

Natural siliceous river sand (NS) with a fineness modulus of 2.7, a saturated surface dry specific gravity of 2.6. It is grading is shown in Table 3 and Fig. 1.

2.1.3. Crushed brick (CB) as fine aggregate replacement

The used crushed bricks had fineness modulus of 2.5, specific gravity of 2.65 and absorption of 1.8 percent. It was prepared by crushing bricks and then controlled to have the same grading of the corresponding natural fine aggregates (sand).

Table 3. Grading of the used fine aggregates.

Sieve size (mm)	Grading % passing	Specification limits (ASTM C33) % passing
4.75	100	95-100
2.36	97.40	80-100
1.18	88.90	50-85
0.61	59.08	25-60
0.31	22.18	5-30
0.16	1.70	0-10

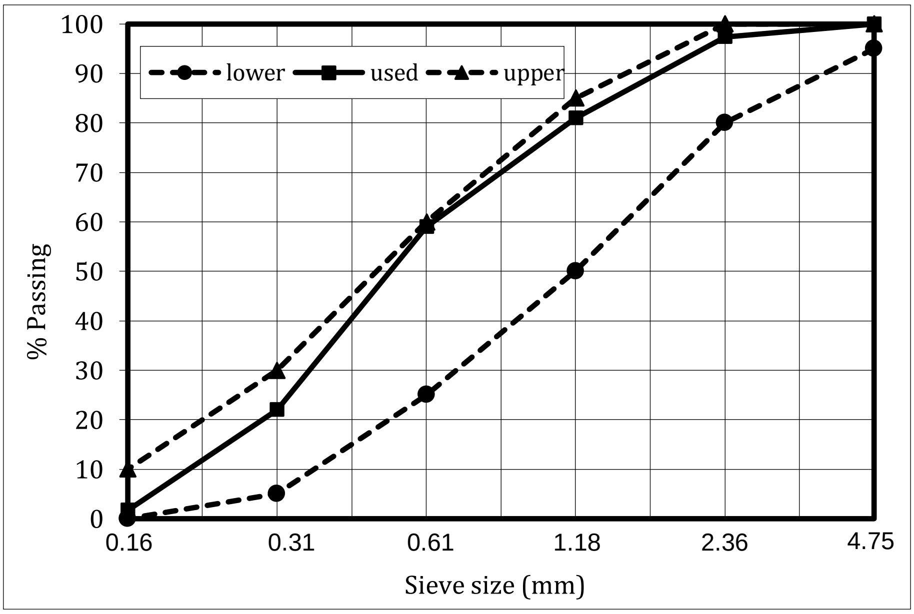

Fig. 1. Grading of the used fine aggregates.

2.1.4. Coarse aggregates

Natural dolomite from Gabal Ataa in Suez area was used as coarse aggregate. The dolomite has a nominal maximum size of about 14 mm. It was washed carefully before mixing to remove any impurities and organic matter which may weaken its bond with the cement paste, also it was immersed in water for about 24 hours, then dried in the air for another 24 hours to reach the saturated and surface dry condition. Grading of the used dolomite is shown in Table 4 and Fig. 2.

2.1.5. Crushed recycled concrete as coarse aggregate replacement

Crushed recycled concrete was collected from old concrete samples in laboratory. It was controlled to maximum nominal size of 14 mm and prepared carefully to be saturated surface dry condition. In addition, its grading was controlled to be as same as that of dolomite coarse aggregates.

The physical properties tests of the four types of aggregates were conducted according to ASTM standards, and their results are shown in Table 5.

Table 4. Grading of the used coarse aggregates.

Sieve size (mm)	Grading % passing	Specification limits (ASTM C33) % passing
20	100	100
14	100	90-100
10	70	40-70
4.75	5.3	0.0-15
2.36	0.0	0.0-5

2.1.6. Water

Ordinary tap water was used in the present research, with cement /water ratio of 0.45.

2.2. Mix design and preparation

The mix design was done in accordance with ACI 211 using the absolute volume method. The W/C ratio was kept constant at 0.45 for all mixes. Eight concrete mixes were prepared with cement content of 400 kg/m^3 in the current research. The first mix (Mc) represents the control mix with natural fine and coarse aggregates. The other three mixes represent the mixes with CB as a partial replacement of sand by ratios of (10, 50, and 100) %. The followed three mixes represents the mixes with CRC replacing the dolomite coarse aggregates by different percentages of 10, 50, and 100%. Based on the compressive strength results of the previous mixes, the last mix was designed to indicate the best possible replacing ratios of CB and CRC in concrete mixes. It represents the mix which contain both replacing materials: 50% of sand aggregate was replaced with CB, and 50% of dolomite coarse aggregate was replaced with CRC. Table 6 shows the details of the mix for each of the eight mixes.

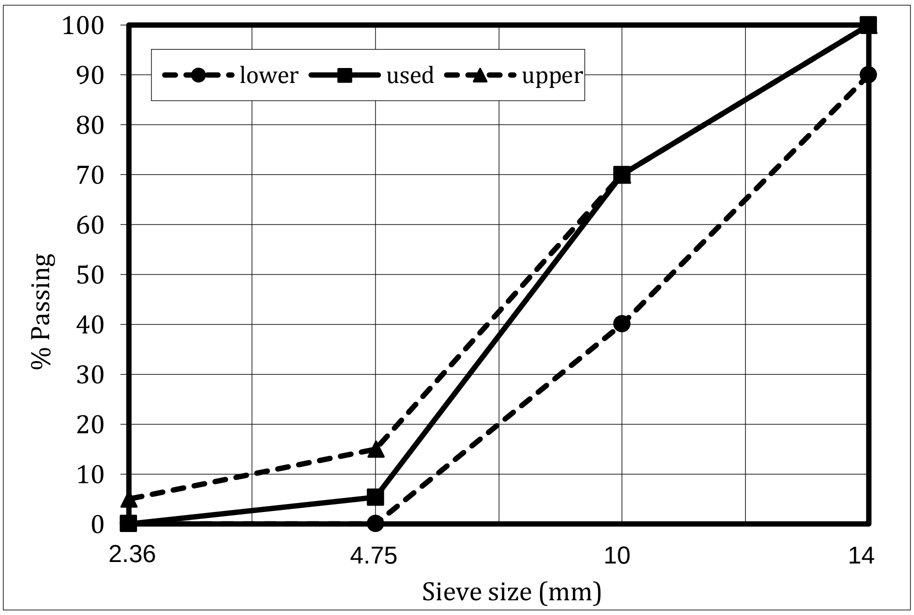

Fig. 2. Grading of the used coarse aggregates.

Table 5. Physical properties of aggregates.

Properties		Volume weight (t/m³) ASTM C29	Specific gravity ASTM C172	Void Ratio %	% Absorption	Fineness modulus
Fine aggregate	NS	1.73	2.6	33.46	2.00	2.7
	CB	1.50	2.5	40.00	5.60	2.5
Coarse aggregate	CD	1.60	2.7	40.60	1.80	6.2
	CRC	1.90	2.7	23.00	0.95	5.5

Table 6. Composition of the concrete mixes (m³).

Mix designation	NS (kg/m³)	CD (kg/m³)	CB (kg/m³)	CRC (kg/m³)	Cement (kg/m³)	W/C ratio
M_c	624	1248	0	0	400	0.45
$M_{(10\%\ B)}$	561.5	1248	62.5	0	400	0.45
$M_{(50\%\ B)}$	312	1248	312	0	400	0.45
$M_{(100\%\ B)}$	0	1248	624	0	400	0.45
$M_{(10\%\ R)}$	624	1123	0	125	400	0.45
$M_{(50\%\ R)}$	624	624	0	624	400	0.45
$M_{(100\%\ R)}$	624	0	0	1248	400	0.45
$M_{(50\%\ B+50\%R)}$	312	624	312	624	400	0.45

2.3. Test specimens

Cubes of dimensions 100 mm were used to determine the compressive strength, cylinders of dimensions 150x 300 mm were used to determine indirect tensile strength (splitting test), and beams of dimensions 100x100x500 mm were used to determine the flexural strength. The concrete mechanical properties were determined at 7, 28, and 56 days after cast of the test specimens. Fig. 3 shows the test specimen during casting.

The specimens were de-molded 24 hours after the casting, and then were cured in water for 7, 28 and 56 days till the time of testing. Three samples were cast for every single test parameter and the average of obtained test results has been recorded. A total of 168 test specimens were tested in the present research.

3. Results and Discussion

Table 7 shows the obtained results for compressive strength, tensile strength, and flexural strength for all mixes.

Fig. 3. Shapes of test molds: cubes, cylinders, and beams.

Table 7. Test results.

Mix Designation	Compressive strength (MPa)	% Change	Tensile strength (MPa)	% Change	Flexural strength (MPa)	% Change
(M_c)	33	0	3.5	0	6.0	0
$M_{(10\% B)}$	38	15.0	4.0	14.5	6.2	3.4
$M_{(50\% B)}$	41	24.0	4.5	28.5	7.0	16.7
$M_{(100\% B)}$	34	3.0	4.2	20.0	6.8	13.4
$M_{(10\% R)}$	37	13.0	4.0	14.3	6.3	5.0
$M_{(50\% R)}$	43	30.0	4.5	28.7	7.5	25.0
$M_{(100\% R)}$	34	3.0	4.3	23.0	7.0	16.7
$M_{(50\% B+50\%R)}$	44	33.4	4.7	34.5	7.8	30.0

3.1. Compressive strength of concrete mixes

The compressive strength results in Table 7 are plotted in Fig. 4, which show that there was an increase in the compressive strength of the specimens when crushed bricks were used to replace the fine aggregates at all percentages below 100% replacement. Moreover, the maximum increase in strength was 23% corresponding to 50% replacement ratio.

When the fine aggregates were totally replaced by crushed bricks (100% replacement), the results showed a slight change in the compressive strength. The increasing in strength is in agreement with the results of previous researches reported in the literature. According to the research of Rashid et al. (2020) and Azunna et al. (2021), the increasing of compressive strength could be referred to the pozzolanic reactivity of the bricks; the $Ca(OH)_2$ crystals in concrete were consumed to generate calcium silicate hydrate (CSH), resulting in enhancing adhesion between the crushed bricks as a fine aggregates and the cement paste.

It can be seen from Table 7 and Fig. 5 that concrete mixes containing different percentages of recycled crushed concrete as a partial replacement of natural coarse aggregates content shows a similar trend but with higher values compared to those of crushed bricks. It is observed that when coarse aggregates were replaced by 50% with crushed concrete, the compressive strength at 7, 28 and 56 days were 30, 43, and 44 MPa, respectively, which represent the highest values of compressive strength. These results could be due to the well preparation of crushed recycled coarse aggregates (CRA); optimal gradation of RCA, shape and texture of RCA, and the quality of RCA that greatly influence the properties of produced concrete. The valuable matter is that the combination of the two types of substitutions maintained the positive effect of them on the compressive strength ($M_{50\%\ B,R}$).

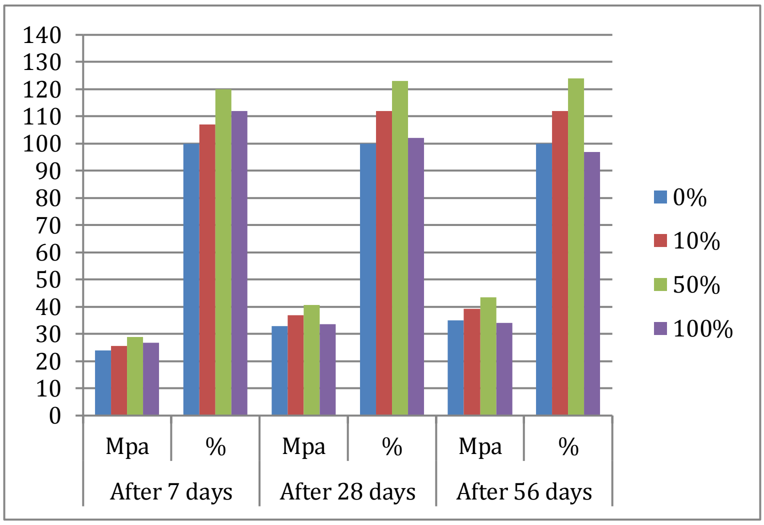

Fig. 4. Results of the compression test for the CB specimens.

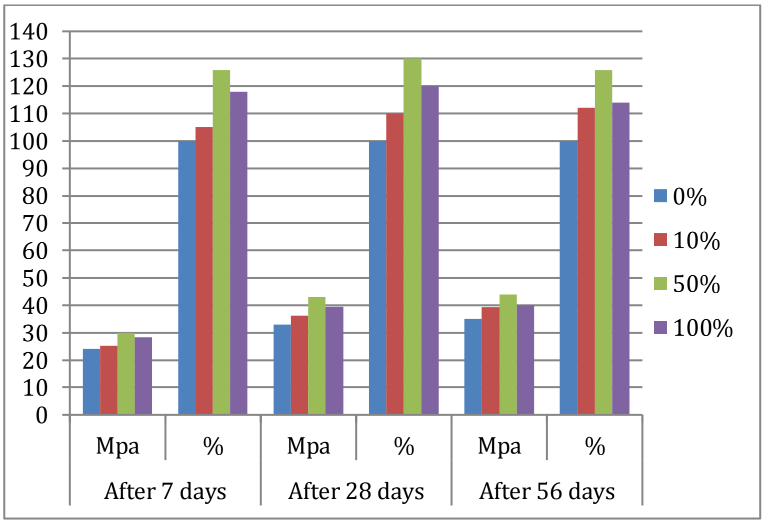

Fig. 5. Results of the compression test for the CRC specimens.

It is also observed that the superior results related to the strength gain were those of $M_{(50\%\ B,R)}$, the mix that incorporating the both types of aggregates alternatives.

It is worthy to study the effect of incorporating CB, and CRC as partial substitutions of fine or coarse aggregates in concrete mixes on compressive strength gain. Therefore, Fig. 6 is plotted to indicate the values of compressive strengths results through 7, 28, 56 days ages of concrete samples. It was found that the rate of compressive strength increased from 7 days until 28 days for all concrete mixes by almost 40%. In addition, the progression of strength continued after 28 days age but with a little increase as the usual of traditional concrete strength gain, meanwhile that CB and CRC maintained the rate of strength gain of concrete even after the standard age (28 days).

3.2. Splitting tensile strength of concrete mixes

The results of splitting tensile strength for all mixes are plotted in Fig. 7. It was observed that when fine aggregate is replaced by 50% crushed bricks, the tensile splitting strength at 28 days age was found to be the greatest value to record 28% increase compared to control mix. For the mixes where coarse aggregate is replaced with a percentage of crushed concrete, the increase in splitting tensile strength was 25% at 50% replacement ratio.

Fig. 8 shows a comparison for the average values of flexural strength of specimens with different percentages of brick-fine aggregate replacements, and CRC – coarse aggregate replacements. Flexure test results for the various concrete specimens are nearly showing similar trends as shown by the splitting tensile strength and compressive strength test results.

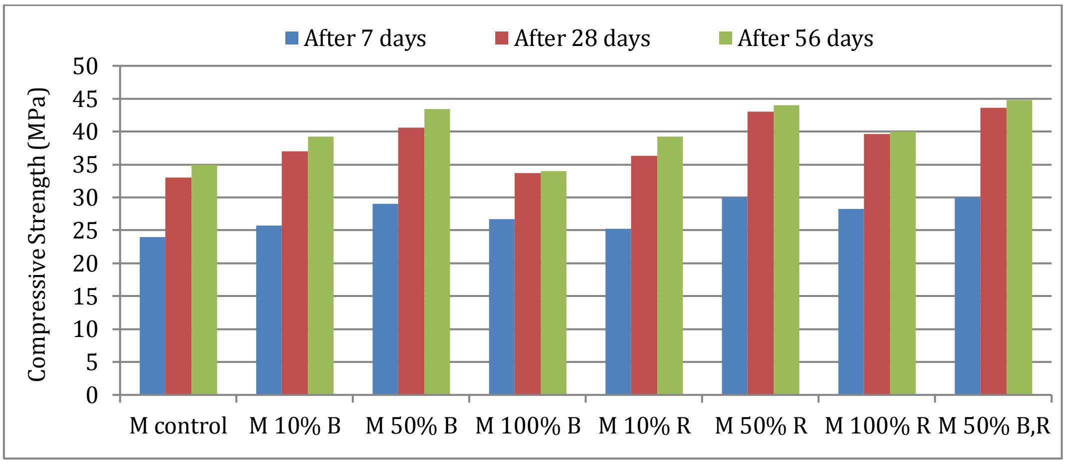

Fig. 6. Effect of the various percentages of CB & CRC on the compressive strength gain.

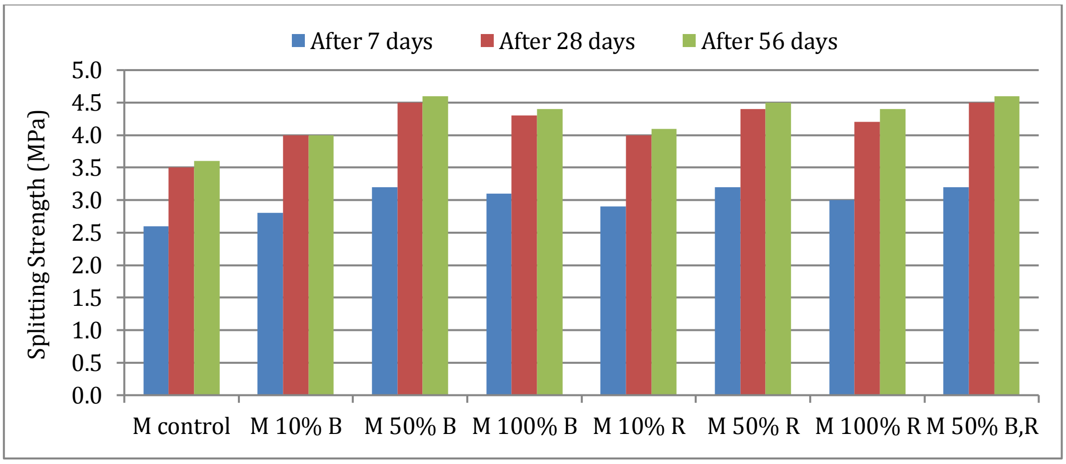

Fig. 7. Effect of the various percentages of CB & CRC on the splitting tensile strength gain.

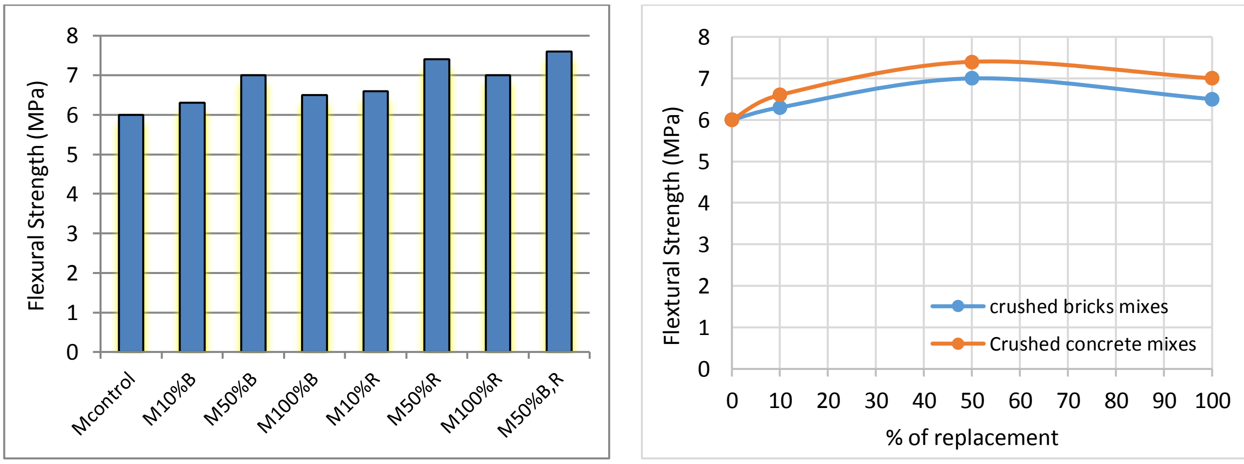

Fig. 8. Flexural strength of concrete mixes after 28 days.

4. Conclusions

Recycled materials were used to preserve the natural materials to produce sustainable concrete. Crushed brick was used to replace the natural fine aggregate and crushed recycled concrete was used to replace the natural coarse aggregate. Different percentages of the replacing materials were considered, namely: 0%, 10%, 50%, and 100%. The effect of the different percentages on the mechanical properties of the produced sustainable concrete was experimentally investigated. Based on the results of the current research the following conclusions could be drawn:

- Wastes such as bricks and concrete can be used as a partial replacement of fine and coarse aggregates in concrete as there was an overall improvement in compressive, tensile and flexural strengths in the mixture with these wastes.

- There is an optimum percentage of replacement that gives the highest effect when substituting fine aggregate with crushed bricks which was found to be 50 % in concrete.
- There is an optimum percentage of replacement that gives the highest effect when substituting coarse aggregate with crushed concrete which was found to be 50 % in concrete.
- At the suggested optimal ratio 50% of fine aggregate with crushed bricks, an increase of 23%, 28%, and 19% was obtained in the compressive, tensile, and flexural strengths, respectively relative to the control specimen.
- At the suggested optimal ratio 50% of coarse aggregate with crushed recycled concrete an increase of 30%, 25%, and 23% was achieved in the compressive, tensile, and flexural strengths, respectively relative to the control specimen.
- The most effective mix was at 50% replacement ratio of coarse aggregate with crushed recycled concrete in combination with 50% replacement ratio of fine aggregate with crushed bricks. The results of this mix showed 32%, 28%, 26% increase in compressive, tensile, and flexural strengths, respectively.

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Conflict of Interest

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Challenge Journal of Concrete Research Letters

Research Article

Efficacies of suggested strength-based prediction models for estimation of compressive and tensile properties of normal concrete

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ABSTRACT

One of the most crucial challenges faced by today's construction industry for a speedy delivery is undeniably the 'time-factor' accompanied by promised quality within the framework of distinct budget. Strength based - Prediction models helps in estimating the early strengths as well as later-stage strength or strength at any age of concrete. Such models assist the structural and execution engineers in arriving at a fair judgement of compressive strength of concrete. A normal practice usually followed by the material testing laboratories and quality assurance cell at site is to assess the cube compressive strength of concrete which is an intrinsic engineering property governing the design and performance phase of structures. It is found from the literature that most of the prediction models that are formulated to estimate the compressive strength of concrete at any age are actually based on cylinder compressive strength of concrete. Therefore, this paper attempts to use some of the suggested prediction models with two sets of data, that is, one by considering experimental results of cube compressive strength found at the age of 7, 14 and 28-days and two by utilizing a conversion value, suitable cylinder compressive strength is obtained. These datasets are thoroughly used in the prediction models to accurately estimate the compressive strength of concrete. Similarly, appropriate prediction models are sought to determine the split tensile strength of normal concretes based on cubic compressive strength and cylinder compressive strength. Particularly, results of the present study showcase that although the prediction models are developed based on cylinder compressive strength, they can agreeably be used on cube strength data as the ratio of (Pi/Ai) obtained is the higher range of 0.85-1.00 and with only an early cube strength result, it is possible to predict an accurate value of split tensile strength of concrete at an age of 28-days. The effectiveness of suggested prediction models through statistical parameters are determined and their efficiencies are found to be in the higher range of 94% to 98%.

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1. Introduction

Concrete is one of the most dynamic and versatile construction material. The performance and durability aspects of concrete largely depends on its compressive strength and is attributed to play a pivotal role in design and construction of any structure. The strength-based prediction models help in obtaining the early age strength or gain of strength at any age without having to wait for the stipulated time period of 28 days (Masood and Murtaza 2015). The later-stage strength characteristics such as durability, permeability, volume firmness are also dependent on compressive strength of concrete. In case of assessing such parameters, it is always desirable to use the strength-based prediction models so that accurate and precise designs are carried out. The evidently known and most common practice is to determine the compressive strength of concrete by casting cubes

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and testing it at the age of 28 days. Some of the recent research articles have documented that the cylinder strength test is the acclaimed process to ensure the precise values of concrete compressive strength and hence the prediction models are actually based on cylinder compressive strength (Monjurul Hasan and Kabir 2011).

The split tensile strength is another distinguished design property which is used in the ductility based designs of concrete structural elements subjected to transverse shear, torsion, differential shrinkage, and thermal strains (Ashwini and Srinivasa Rao 2021). The tensile strength determines the load-bearing behaviour of concrete structures by taking the compressive strength as a design parameter (Reinhardt 2013). This essentially proves that both compressive strength and the tensile strength supremely affects one another and dictates the performance and response of structures.

The assessment of these strength-related parameters are usually carried out in material testing laboratories and are studied as specimens cast into cubes or cylinders. Hence, the estimation of these governing properties becomes the premise of the present study wherein a few suggested prediction models are sought to predict the cube compressive strength on the basis of cylinder-based prediction models.

2. Review of the Recent Research

In the recent past, several researchers have attempted to predict the compressive and tensile strength of concrete based on mathematical and computation models considering the basic constituents of concrete such as cement, fine aggregates, coarse aggregates, water content, water-cement ratio and in some cases, the physical properties such as fineness modulus of sand and size ratio of components of coarse aggregates are also accounted. Some of the noteworthy research investigations are documented in the paragraphs below.

2.1. Prediction models for compressive strength

Chopra et al. (2014) carried out statistics based mathematical analysis by developing multiple non-linear regression models for predicting the compressive strength of concrete based on experimental work on concrete mixes proportioned for medium and high workability at different curing ages of 28, 56 and 91 days. The multivariable power equations were developed and the study suggested two models for medium and high workable concrete mixes. Co-efficient of determination (COD) and Root Mean Square Error (RMSE) were chosen as the statistical parameters to evaluate the effectiveness of the predicted models and they were found to 95% accurate with experimental data. Masood and Murtaza (2014) presented analytical models that were developed by using the data of concrete strengths obtained from the experimental results of testing cylinders. Two models were proposed to predict the compressive strength of concrete up to 28-days using the 7-day compressive strength. The research work suggested that of the four cement compounds, as C_3S and C_2S largely contribute to the early and long-term strengths of cement, hence they were included in the prediction models as 'logical variables' along with the fineness of cement. Also, for the sake of simplicity and owing to the fact that strength properties are majorly influenced by the composition of C_3S and fineness of cement up to 7-days, the 7-days compressive strength was included as one of the leading parameters in both the prediction model. Regression analysis using the least square method were used to predict the important two-defining parameters α and β correlating the effects of chemical composition of cement, specifically, C_3S and C_2S and fineness of cement. The proposed models provided a good correlation with experimental data and were validated with results of several types of cement brands reported in literature. Chopra et al. (2015) made efforts to develop prediction models to estimate the concrete compressive strength using the two data mining techniques, such as, Artificial Neural Networks (ANN) and Genetic Programming (GP). The study reported a comparison of predicted results from these two models and inferred that the model developed by using ANN with a training function Levenberg-Marquardt (LM) yielded better results and lesser value of RMSE, meaning that the predicted values are mostly precise with the experimental results. Ahsanul et al. (2012) suggested a simple mathematical equation comprising of two constants and a variable, age of concrete in days, based on rational polynomial to predict the compressive strength of concrete at 28-days from 7-days early strength. The constants '*p*' associated with stress unit and 'q' as unit in days. The model proposed is a simple equation where the compressive strength of any data can be determined from only one test result input data. It was observed that the constants *p*, *q* and strength at a particular day, $f'_{c,D}$ maintained a correlation of polynomial surface (especially fitted well as a second degree polynomial surface equation) and facilitated to express constant *p* in-terms of *q*. The general form of correlation equation was found as : $p = m(f'_{cD})^r$, with '*m*' equal to 3.0 and 2.5 respectively for 7 and 14 days and '*r*' equal to 0.80.

The effectiveness of the predicted models were determined using RMSE, Mean absolute error (MAE) and the efficiency up to 92% were reported. The suggested model predicted similar results when compared with the experimental data and mentioned that the predicted tool could be used to estimate the strength of concrete at any age. Metwally (2013) carried out similar studies on predicting the compressive strength of concrete at any age based on statistical analysis. The prediction model put forth two constants, A and B in the equation which were considered as a characteristic property for a concrete mix. The constants A and B were introduced as a components of a rate of strength gain constant and grade strength constant respectively. The research work emphasized on development of these constants based on thorough understanding of strength developments of pure clinker compounds, the C_3S, C_2S, C_3A and C_4AF. The research study implied that for a given degree of hydration, the strength increases in the order of $C_3A < C_4AF < C_2S < C_3S$, signifying the prevailing differences in the intrinsic strengths of hydrates formed in the hydration of clinker compounds. Hence, the study specified that based on cement composition, the strength development of pure clinker minerals is found to be in the form of $f_t = A \ln(t) + B$ with correlation coefficient approaching unity. The analysis revealed that the proposed predicted model gave highly accurate results following the concrete mixes with no additives and mixes with additives such as silica fume and nano silica when cured at normal temperature and in water.

2.2. Prediction models for split tensile strength

Mehrdad and Ramezan (2021) examined the behaviour of normal and steel fiber reinforced concrete to predict the tensile strength when exposed to high temperatures as it greatly influences on the performance characteristics of concrete structures especially when the members are subjected to high temperatures. The main objective of this work was to aid a broader application of steel fibers specifically with fire resistant structures and the proposed prediction model would help in estimating the tensile strength under high-temperature exposure conditions as high as 28°C to 800°C. The study aimed at predicting tensile strength based on regression analysis for both normal concrete and steel fiber reinforced concrete separately and these formed the basis for developing tensile strength expressions when normal concrete and steel FRC exposed to high elevated temperatures. Further, it showed that the compressive strength has a great impact on the tensile strength of concrete, where an increase of compressive strength from 20.1 MPa to 84.45 MPa improves the tensile strength by 169.4% at ambient temperature and an average deviation of experimental results with the predicted model showed about 7.53% indicating high accuracy and validating the predicted tensile strength model. Açıkgenç et al. (2015) conducted experimental investigations to develop relation between splitting tensile strength and flexural strengths of plain concrete and steel fiber-reinforced concrete. The study focused on estimating the flexural strength by using a relation with splitting tensile strength as the former requires testing heavy beams while the latter needs standard cubes or cylinders as specimens. In this study, the functions of compressive strength, split tensile strength and flexural strengths for varying volume fraction of steel fibers are defined in terms of Abram's law comprising of water-cement ratio and two empirical constants. The relations of compressive-splitting tensile strength and compressive-flexural strengths yielded a strong correlation of 95% and 96% respectively. Ashwini and Srinivasa Rao (2021) carried out research investigations on determination of correlation between compressive and splitting tensile strength of concrete using alccofine and nano silica based on prediction model – power type regression equation and validating them with the experimental results with an age of 28-days curing time. Three concrete grades of M40, M60 and M80 were selected with mixes having no additives, with alccofines and with both alccofines and nano silica. It was observed that split tensile strength for all grades of concrete increased with an increase in compressive strength. The proposed model gave a good correlation of R^2 of 95.45% and the results of error analysis on the model showed lowest error results of the model proving its accuracy. Mane et al. (2019) conducted experimental investigations on use of pozzolanic materials such as fly ash, GGBS, silica fume and metakaolin as a partial replacement to cement along with replacement of natural sand by manufactured sand to determine the tensile strength of concrete. The experimental results obtained were checked with a prediction model developed based on artificial neural networks (ANN) at an age of 28 days. In all the cases of incremental replacement studies, the predicted model showed almost similar results as that of the experiments with high R^2 value in the range of 0.94 – 0.96. Jinping et al. (2019) conducted rigorous experiments to evaluate the concrete cube splitting tensile strength based on the curing age and aging degree of concrete. The study related to the significance of maturity concept of concrete wherein along with time, temperature of curing also plays an important role and that the age degree has a direct influence on splitting tensile strength of concrete indicating that a larger difference of age degree results in larger difference in split tensile strength of concrete. A predictor model was developed based on the experimental results of cubic split tensile strength of 150x150x150 mm and a comparison with experimental data showed that the intensity of increase in split tensile strength of concrete is rapid for the first 7-days and the intensity of 70% is reached up to an age of 28-days.

It is clear from this extensive study on literature, that there is a need to find out whether the available prediction models (which are based on cylinders) are capable enough in accurately predicting the compressive strength of concrete when the type of specimens cast are cubes and its implications on predictions of cubic and cylinder split tensile strength of concrete. Therefore, these pointers essentially forms the motivation of the present investigation which is discussed in detail in the following section.

3. Present Investigation

3.1. Scope of the study

It has already been well-highlighted that use of strength based - prediction models will help in saving time in order to obtain nearly accurate estimation of probable development of strength after a certain curing time. As a normal practice, it is seen that usually compressive strength of concrete is determined by casting them into cubical moulds of either 150 mm or 100 mm in size. On the other hand, it is finely indicated in several research articles that the prediction models are based on cylinder compressive strength as they are found to be far more accurate and precise. Hence, there is need to have clear understanding of these aspects before using the prediction models. Therefore, the objectives of the present investigation are summarized as follows –

- Prediction of cube compressive strength using prediction models (1 to 4) at 14 and 28-days using 7-days test results and validating them with experimental results.

- Prediction of cylinder compressive strength by using an appropriate conversion factor to cube strength and then using the prediction models to estimate the strength of 14 and 28-days.
- Prediction of cubic and cylinder split tensile strength by various prediction models suggested in literature.
- Estimation of effectiveness of prediction models using simple statistical error analysis.

3.2. Methodology

The present investigation is aligned with use of suggested prediction models mentioned in Table 1 and are based on literature studies (covered in previous section) to predict the compressive and split tensile strength of normal concrete. In this context, around 16 experimental results of cube compressive strength of normal concrete of M25 grade, cured and tested for compressive strength in accordance with IS: 516–1959 (reaffirmed in 2004) at an age of 7, 14 and 28-days in concrete material testing laboratory of Dept. of Civil Engineering, B.M.S College of Engineering, Bengaluru, Karnataka are considered.

It is to be noted here that the developed prediction models of referred literature are based on cylinder compressive strength of concrete. Based on several literature studies, a conversion factor suggested by relevant research studies of João et al. (2019) and David and Gongkang (1995) of 0.81 is adopted to convert the cube compressive strength to appropriate cylinder compressive strength of concrete. This value of conversion factor is based on computations of model accounting as both deterministic (considering practical conversions of test data) and probabilistic (considering normal distributions) in nature for normal concretes with natural aggregates. These estimated values along with experimental data considered for the present study are shown in Table 2. The use of suggested prediction models for compressive strength and split tensile strength are abbreviated in the series of C_p – 1, 2, 3, 4 and T_p – 1, 2 respectively. For each case of use of suggested prediction model (P_i), cube compressive strength at 28-days is obtained and verified with experimental data (A_i) and correspondingly cylinder compressive strength is estimated and again verified with the predicted data.

Table 1. Summary of prediction models based on literature.

Prediction models for compressive strength		
Model Code	Prediction model	Notations
Cp-1 (Ahsanul et al. 2012)	$f'_{C,D} = \frac{D}{D+q}.p$ $p = 3.0\left(f'_{C,7}\right)^{0.8}$	$f'_{C,D}$ = strength of concrete at D^{th} day, D = No. of days, p and q are constants determined by using regression analysis.
Cp-2 (Metwally 2014)	$f_t = A\ln(t) + B$ $B = 0.005(f_c)^{2.20}$ $A = 1.4035\ln(B) + 2.9956$	f_t = compressive strength at age (t) days, f_c = 28-day compressive strength, B = is the grade constant (R^2 = 0.91), A = is the rate constant (R^2 = 0.98).
Cp-3 (Masood and Murtaza 2015)	$f_c = 0.56 \times f_{c,7} \times t_n^{0.29}$ where $\{7 < t_n \leq 28\}$	f_c = compressive strength of concrete beyond 7-day strength, $f_{c,7}$ = 7- day compressive strength of concrete, t_n = age of concrete at which strength of concrete is to be predicted (n = 8,…,28), $f_{c,t}$ = strength of concrete at time (t) beyond 28 days.
Cp-4 (Masood and Murtaza 2015)	$f_{c,t} = f_{c,7} \times \frac{t_n}{(3.2 + 0.58t)}$ where $\{7 < t_n \leq 28\}$	
Prediction models for split tensile strength		
Using cube compressive strength		
Tp-1 (Jinping et al. 2019)	$f_{cp} = 0.25 \times f_{cu}(t,T)^{0.7}$ $f_{cu}(t,T) = [0.2134 \times \ln(T) + 0.3122] \times \left[1 + 0.05968 \times \left(1 - \frac{20t}{T}\right)\right] f_{cu}$	f_{cp} = concrete cubic split tensile strength of different curing and age degree, t = curing age of the specimen (in days), T = age degree of the specimens (°C.d), f_{cu} = 28-days cube compressive strength, f_{cu} (t,T) = is the cubic strength prediction based on age and age degree
Using cylinder compressive strength		
Tp-2$_i$ (Mehrdad and Ramezan 2021)	$f_t = 0.167 f_c^{0.821}$	f_t = split tensile strength of concrete, f_c = cylinder compressive strength, MPa
Tp-2$_{ii}$ (Mehrdad and Ramezan 2021)	$f_t = 0.188 f_c^{0.84}$	
Tp-2$_{iii}$ (Mehrdad and Ramezan 2021)	$f_t = 0.21 f_c^{0.83}$	
Tp-2$_{iv}$ (Ramadoss 2014)	$f_t = 0.12 f_c^{0.95}$	
Tp-2$_v$ (Mehrdad and Ramezan 2021)	$f_t = 0.56 f_c^{0.5}$	

3.2.1. Use of prediction models for estimating compressive strength of concrete

The experimental data of cube compressive strength obtained at 7, 14 and 28 days considered for the present study are presented in Table 2. In addition, the cylinder strength is estimated as 0.81 times cube strength value obtained at 7, 14 and 28 days.

Cp-1. In the present study, using the experimental data of cube strength and estimated cylinder strength at 7-days (Table 2), constants are calculated and then 14th and 28-days compressive strengths are predicted using the expressions mentioned in Table 1. The results of use of Cp-1 in the present study are shown in Table 3.

Cp-2. The prediction model requires 28-days strength as an input value to determine the constants A (rate of strength gain constant and B (grade constant). Hence, in the present study, the experimental data of cube strength and estimated cylinder strength at 28-days are considered. From this, constants B and A are calculated and then 7th and 14-days strength are computed along with corresponding ratios of predicted to actual values. The results are shown in Table 4.

Table 2. Experimental data of cube strength and estimated cylinder strength considered for present study.

	Experimental cube strength in days (MPa)			Estimated cylinder strength in days (MPa) by using conversion value of 0.81				Experimental cube strength in days (MPa)			Estimated cylinder strength in days (MPa) by using conversion value of 0.81		
Sp. No	7	14	28	7	14	28	Sp. No	7	14	28	7	14	28
1	22.40	28.40	35.50	18.14	23.00	28.76	9	28.91	32.84	41.05	23.42	26.60	33.25
2	23.74	27.76	34.70	19.23	22.49	28.11	10	29.83	32.54	40.68	24.16	26.36	32.95
3	22.01	29.52	36.90	17.83	23.91	29.89	11	19.12	21.80	27.25	15.49	17.66	22.07
4	24.23	30.96	38.70	19.63	25.08	31.35	12	19.05	22.26	27.82	15.43	18.03	22.53
5	24.30	30.00	37.50	19.68	24.30	30.38	13	19.16	22.62	28.27	15.52	18.32	22.90
6	21.68	28.56	35.70	17.56	23.13	28.92	14	19.59	23.33	29.16	15.87	18.90	23.62
7	26.40	30.52	38.15	21.38	24.72	30.90	15	19.52	23.82	29.78	15.81	19.30	24.12
8	25.60	31.68	39.60	20.74	25.66	32.08	16	19.63	23.08	28.85	15.90	18.69	23.37

Mean = 34.35/27.82 MPa (28-days strength of cube/cylinder), COV = 14.53

Table 3. Results of the prediction model: Cp-1.

	Using experimental cube strength in days (MPa)						Using estimated cylinder strength in days (MPa)					
	Constants		P_i	Ratio (P_i/A_i)	P_i	Ratio (P_i/A_i)	Constants		P_i	Ratio (P_i/A_i)	P_i	Ratio (P_i/A_i)
Sp. No	p	q	14		28		p	q	14		28	
1	36.08	4.28	27.64	0.97	31.30	0.88	30.49	4.76	22.75	0.99	26.06	0.91
2	37.80	4.15	29.16	1.05	32.93	0.95	31.94	4.63	24.01	1.07	27.41	0.98
3	35.58	4.32	27.20	0.92	30.83	0.84	30.06	4.80	22.38	0.94	25.66	0.86
4	38.42	4.10	29.72	0.96	33.52	0.87	32.46	4.58	24.46	0.98	27.90	0.89
5	38.51	4.09	29.80	0.99	33.60	0.90	32.54	4.57	24.53	1.01	27.97	0.92
6	35.15	4.35	26.82	0.94	30.43	0.85	29.70	4.84	22.07	0.95	25.32	0.88
7	41.15	3.91	32.17	1.05	36.11	0.95	34.77	4.38	26.48	1.07	30.06	0.97
8	40.15	3.98	31.27	0.99	35.16	0.89	33.92	4.45	25.74	1.00	29.27	0.91
9	44.25	3.72	34.97	1.06	39.07	0.95	37.39	4.18	28.80	1.08	32.54	0.98
10	45.38	3.65	36.00	1.11	40.15	0.99	38.34	4.11	29.64	1.12	33.43	1.01
11	31.79	4.64	23.88	1.10	27.27	1.00	26.86	5.14	19.65	1.11	22.69	1.03
12	31.70	4.65	23.80	1.07	27.19	0.98	26.78	5.15	19.58	1.09	22.62	1.00
13	31.84	4.63	23.93	1.06	27.32	0.97	26.90	5.14	19.68	1.07	22.74	0.99
14	32.42	4.58	24.42	1.05	27.86	0.96	27.39	5.08	20.09	1.06	23.18	0.98
15	32.32	4.59	24.34	1.02	27.77	0.93	27.31	5.09	20.03	1.04	23.11	0.96
16	32.47	4.58	24.47	1.06	27.91	0.97	27.43	5.08	20.13	1.08	23.22	0.99

Mean = 31.6/26.4 MPa (28-days strength of P_i - cube/cylinder), COV = 13.4

Table 4. Results of the prediction model: Cp-2.

Sp. No	Using experimental cube strength in days (MPa)						Using estimated cylinder strength in days (MPa)					
	Constants		P_i	Ratio (P_i/A_i)	P_i	Ratio (P_i/A_i)	Constants		P_i	Ratio (P_i/A_i)	P_i	Ratio (P_i/A_i)
	B	A	7		14		B	A	7		14	
1	12.87	6.58	25.67	1.15	28.70	1.01	8.09	5.93	19.63	1.08	22.49	0.98
2	12.24	6.51	24.91	1.05	27.68	1.00	7.70	5.86	19.10	0.99	21.72	0.97
3	14.01	6.70	27.05	1.23	30.29	1.03	8.81	6.05	20.58	1.15	23.63	0.99
4	15.56	6.85	28.88	1.19	32.03	1.03	9.79	6.20	21.84	1.11	24.78	0.99
5	14.52	6.75	27.65	1.14	30.65	1.02	9.13	6.10	21.00	1.07	23.82	0.98
6	13.03	6.60	25.87	1.19	29.02	1.02	8.19	5.95	19.77	1.13	22.74	0.98
7	15.08	6.80	28.31	1.07	31.14	1.02	9.48	6.15	21.46	1.00	24.10	0.97
8	16.36	6.92	29.83	1.17	32.90	1.04	10.29	6.27	22.49	1.08	25.35	0.99
9	17.71	7.03	31.39	1.09	34.26	1.04	11.14	6.38	23.55	1.01	26.21	0.99
10	17.36	7.00	30.99	1.04	33.73	1.04	10.92	6.35	23.28	0.96	25.82	0.98
11	7.19	5.76	18.41	0.96	20.95	0.96	4.52	5.11	14.47	0.93	16.94	0.96
12	7.53	5.83	18.87	0.99	21.48	0.97	4.73	5.18	14.81	0.96	17.34	0.96
13	7.80	5.88	19.23	1.00	21.88	0.97	4.90	5.23	15.08	0.97	17.64	0.96
14	8.35	5.97	19.97	1.02	22.66	0.97	5.25	5.32	15.61	0.98	18.20	0.96
15	8.74	6.04	20.49	1.05	23.26	0.98	5.50	5.39	15.98	1.01	18.65	0.97
16	8.15	5.94	19.71	1.00	22.36	0.97	5.13	5.29	15.42	0.97	17.98	0.96

Mean = 35.19/26.87 MPa (28-days strength of P_i - cube/cylinder), COV = 17.69/17.16

Cp-3. The prediction model requires 7-days compressive strength and any age/day strength beyond 7-days can be calculated by the respective relation mentioned in Table 1. It is reported that the coefficients of the regression equation, α = 0.56 and β = 0.29 are determined as function of cement type which in turn is represented by the chemical and compound composition and fineness.

Cp-4. The equation represented in this prediction model is slated to be a modification to ACI 209R- 92 code which is used to predict the strength at any time, t beyond the age of 28-days where α and β range from 0.05 - 9.25 and 0.67 - 0.98 respectively. It is documented that the average values of α and β complying with the (fineness + C_3S content) and total silicate content (C_3S+ C_2S) of cement composition is equal to 3.2 and 0.58 respectively.

Table 5. Results of the prediction model: Cp-3.

Sp. No	Using experimental cube strength in days (MPa)						Using estimated cylinder strength in days (MPa)					
	Constants		P_i	Ratio (P_i/A_i)	P_i	Ratio (P_i/A_i)	Constants		P_i	Ratio (P_i/A_i)	P_i	Ratio (P_i/A_i)
	α	β	14		28		α	β	14		28	
1	0.56	0.29	26.97	0.95	32.97	0.93	0.56	0.29	21.84	0.95	26.71	0.93
2			28.58	1.03	34.94	1.01			23.15	1.03	28.30	1.01
3			26.50	0.90	32.40	0.88			21.46	0.90	26.24	0.88
4			29.17	0.94	35.66	0.92			23.63	0.94	28.89	0.92
5			29.25	0.98	35.77	0.95			23.69	0.98	28.97	0.95
6			26.10	0.91	31.91	0.89			21.14	0.91	25.85	0.89
7			31.78	1.04	38.86	1.02			25.74	1.04	31.47	1.02
8			30.82	0.97	37.68	0.95			24.96	0.97	30.52	0.95
9			34.80	1.06	42.55	1.04			28.19	1.06	34.47	1.04
10			35.91	1.10	43.91	1.08			29.09	1.10	35.56	1.08
11			23.02	1.06	28.14	1.03			18.64	1.06	22.79	1.03
12			22.93	1.03	28.04	1.01			18.58	1.03	22.71	1.01
13			23.07	1.02	28.20	1.00			18.68	1.02	22.84	1.00
14			23.58	1.01	28.83	0.99			19.10	1.01	23.36	0.99
15			23.50	0.99	28.73	0.96			19.03	0.99	23.27	0.96
16			23.63	1.02	28.89	1.00			19.14	1.02	23.40	1.00

Mean = 33.6/27.2 MPa (28-days strength of P_i - cube/cylinder), COV = 15.5

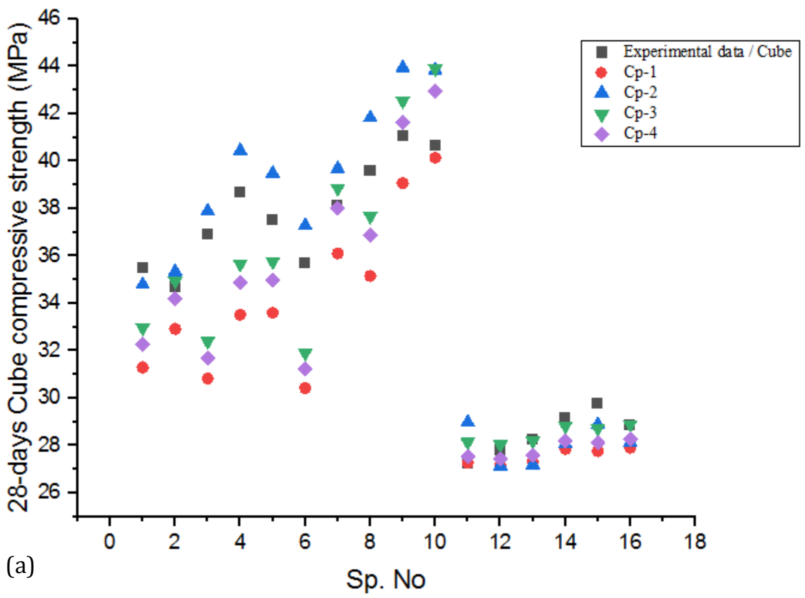
Table 6. Results of the prediction model: Cp-4.

Sp. No	Using experimental cube strength in days (MPa)						Using estimated cylinder strength in days (MPa)					
	Constants		P_i	Ratio (P_i/A_i)	P_i	Ratio (P_i/A_i)	Constants		P_i	Ratio (P_i/A_i)	P_i	Ratio (P_i/A_i)
	α	β	14		28		α	β	14		28	
1	3.20	0.58	27.70	0.98	32.26	0.91	3.20	0.58	22.44	0.98	28.45	0.99
2			29.36	1.06	34.19	0.99			23.78	1.06	27.81	0.99
3			27.22	0.92	31.70	0.86			22.05	0.92	29.57	0.99
4			29.97	0.97	34.90	0.90			24.27	0.97	31.01	0.99
5			30.05	1.00	35.00	0.93			24.34	1.00	30.05	0.99
6			26.81	0.94	31.23	0.87			21.72	0.94	28.61	0.99
7			32.65	1.07	38.02	1.00			26.45	1.07	30.57	0.99
8			31.66	1.00	36.87	0.93			25.65	1.00	31.74	0.99
9			35.75	1.09	41.64	1.01			28.96	1.09	32.90	0.99
10			36.89	1.13	42.97	1.06			29.88	1.13	32.60	0.99
11			23.65	1.08	27.54	1.01			19.15	1.08	21.84	0.99
12			23.56	1.06	27.44	0.99			19.08	1.06	22.30	0.99
13			23.70	1.05	27.60	0.98			19.19	1.05	22.66	0.99
14			24.23	1.04	28.22	0.97			19.62	1.04	23.37	0.99
15			24.14	1.01	28.12	0.94			19.55	1.01	23.87	0.99
16			24.28	1.05	28.27	0.98			19.66	1.05	23.12	0.99

Mean = 32.87/27.53 MPa (28-days strength of P_i - cube/cylinder), COV = 15.46/14.53

In the present investigation, the experimental cube and estimated cylinder 7-days strength are utilized and strength at 14th and 28-days are predicted and corresponding (P_i/A_i) ratio are determined separately by using Cp-3 and Cp-4. The results are shown in tables 5 and 6 respectively. The mean and co-efficient of variation (COV) of predicted results (28-days) are computed for each predicted model and the results are mentioned below each of them

The experimental data of cube and estimated cylinder compressive strengths of all the specimens with the results obtained from the above four considered prediction models are plotted graphically presented below as Fig. 1(a-b), respectively. It can be seen from these graphs that the nearly almost all the results obtained through the predicted models match with the experimental cube and estimated cylinder compressive strength data implying the effectiveness of the prediction models.



(a)

Fig. 1. (continued)

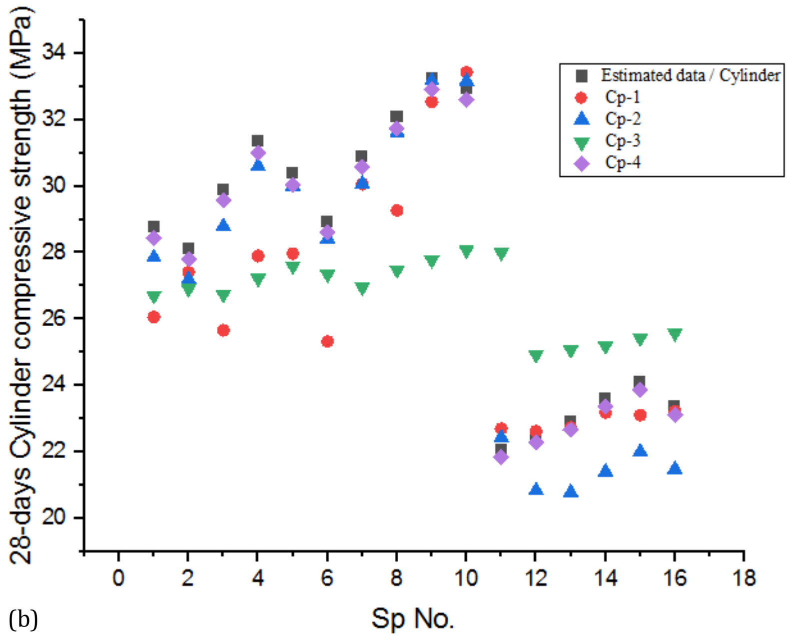


Fig. 1. (a) Experimental cube strength data with results of prediction models at 28-days; (b) Cylinder strength data with results of prediction models at 28-days.

The statistical error analysis are performed to understand the efficacies of considered predicted model in obtaining the cube and cylinder compressive strengths by using the following expressions.

- Mean absolute error = $MAE = \frac{1}{n}\sum_{i=1}^{n}|P_i - A_i|$
- Root mean square error = $RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(P_i - A_i)^2}$
- Efficiency = $EF = (1 - (\frac{1}{n}\sum_{i=1}^{n}\frac{|P_i - A_i|}{A_i})) \times 100\%$

The results of these statistical parameters obtained from each of the predicted model are shown in Table 7.

Table 7. Statistical error analysis on predicted cube and cylinder compressive strength results.

Statistical parameters	Predicted results of cube compressive strength							
	Cp-1		Cp-2		Cp-3		Cp-4	
	14	28	7	14	14	28	14	28
RMSE	1.65	3.20	2.72	0.83	1.62	2.13	1.82	2.45
MAE	1.45	2.58	2.12	0.76	1.33	1.61	1.47	1.87
EF (%)	94.67	92.82	91.04	97.25	95.39	95.59	94.73	94.78
Avg (*Pi*/*Ai*)	1.03	0.93	1.08	1.00	1.00	0.98	1.03	0.96
(Min - Max)	0.92-1.11	0.84 -1.00	0.96-1.23	0.96-1.04	0.90-1.10	0.88-1.08	0.92-1.13	0.86-1.06
Statistical parameters	Predicted results of cylinder compressive strength							
	Cp-1		Cp-2		Cp-3		Cp-4	
	14	28	7	14	14	28	14	28
RMSE	1.53	2.05	1.30	0.57	1.31	1.72	1.47	0.30
MAE	1.30	1.52	1.00	0.55	1.07	1.31	1.19	0.29
EF (%)	94.03	94.81	94.56	94.72	95.39	95.59	94.73	98.95
Avg (*Pi*/*Ai*)	1.04	0.95	1.03	0.97	1.00	0.98	1.03	0.99
(Min - Max)	0.94-1.12	0.86-1.03	0.93-1.15	0.96-0.99	0.90-1.10	0.88-1.08	0.92-1.13	0.99-0.99

3.2.2. Use of prediction model for estimating splitting tensile strength of concrete

In the section based on literature studies, two distinct type of models are chosen. The first one, Tp-1 presents cubic split tensile strength which is centered on cubic compressive strength and the second type of models, that is, Tp-2$_{i \text{ to } v}$ represents a group of similar equations developed on the basis of regression analysis and relies on cylinder compressive strength.

Tp-1. This model requires 28-days cube compressive strength of concrete as an input value. It is reported that along with curing age in days, age degree (°C.d) is another crucial parameter that is involved which accounts to the maturity concept of concrete. Hence in the present study, in order to calculate curing age and age degree, 28-days and 25°C of prevalent temperature are considered. Experimental data of 28-days cube compressive strength and median (as the obtained results appear to be skewed) of 28-days results of predicted models from Cp-1 to Cp-4 are considered separately to predict cubic split tensile strength of concrete and the outcomes are compared as shown in Table 8.

Tp-2$_{i, ii, iii, iv, v}$. In this model, prediction of split tensile strength based on regression equations which are developed by several researchers in recent times for normal (plain) concretes based on cylinder compressive strength are considered. The estimated cylinder strength and median of predicted results from Cp-1 to Cp-4 at 28-days are considered and used as an input value f_c in the above mentioned regression equations to predict the split tensile strength of concrete and the obtained results are compared.

It can be seen from both tables 8 and 9 that the results of predicted split tensile strength, both cubic and cylinder have yielded almost similar results when compared with the experimental/estimated data. The lower value of co-efficient of variation (COV) highlights the advantage and efficiency of prediction models. A comparison of predicted cubic and cylindrical splitting tensile strength of concrete results is shown graphically in Fig. 2.

4. Summary of Findings

The present study focuses on effective use of the predicted models for estimating the compressive strength and split tensile strength of concrete which are suggested in several literatures. The predicted results of each model comprising of cube and cylinder strength when compared with the experimental data are found to be close to each other. The effectiveness of these prediction models are summarized in Table 7 and it can be seen from this table that the statistical parameters, viz., RMSE and MAE are mostly found to be on the lower side, that is, between 1.3-3.20, indicating high efficiencies in the order of 94% to 98% of the prediction models. This proves that although the prediction models are developed based on cylinder compressive strength, they can still be effectively and efficiently adopted to predict the cube compressive strength.

Table 8. Results of Tp-1.

Sp. No	Experimental data, f_c (MPa)	Predicted cubic split tensile strength, f_{cp} (MPa)	Median of predicted results, f_c (MPa)	Predicted cubic split tensile strength, f_{cp} (MPa)
1	35.50	3.13	32.62	2.95
2	34.70	3.08	34.57	3.07
3	36.90	3.21	32.05	2.92
4	38.70	3.32	35.28	3.11
5	37.50	3.25	35.38	3.12
6	35.70	3.14	31.57	2.89
7	38.15	3.29	38.44	3.30
8	39.60	3.37	37.28	3.23
9	41.05	3.45	42.10	3.51
10	40.68	3.43	43.41	3.59
11	27.25	2.61	27.84	2.65
12	27.82	2.65	27.31	2.62
13	28.27	2.68	27.46	2.63
14	29.16	2.74	28.15	2.67
15	29.78	2.78	28.42	2.69
16	28.85	2.72	28.20	2.68
Mean		3.05		2.98
COV		10.0		10.7

Table 9. Results of Tp-2$_{i, ii, iii, iv, v}$.

Sp. No	Estimated cylinder 28-days strength, f_c (MPa)	Tp-2$_i$	Tp-2$_{ii}$	Tp-2$_{iii}$	Tp-2$_{iv}$	Tp-2$_v$	Predicted median cylinder 28-days strength, f_c (MPa)	Tp-2$_i$	Tp-2$_{ii}$	Tp-2$_{iii}$	Tp-2$_{iv}$	Tp-2$_v$
1	28.76	2.63	3.16	3.41	2.92	3.00	27.28	2.52	3.02	3.27	2.77	2.92
2	28.11	2.58	3.10	3.35	2.85	2.97	27.61	2.55	3.05	3.30	2.81	2.94
3	29.89	2.72	3.26	3.52	3.03	3.06	27.52	2.54	3.04	3.29	2.80	2.94
4	31.35	2.83	3.40	3.66	3.17	3.14	29.75	2.71	3.25	3.51	3.01	3.05
5	30.38	2.75	3.31	3.57	3.07	3.09	29.48	2.69	3.23	3.48	2.99	3.04
6	28.92	2.64	3.17	3.43	2.93	3.01	27.14	2.51	3.01	3.25	2.76	2.92
7	30.90	2.79	3.36	3.62	3.12	3.11	30.33	2.75	3.30	3.57	3.07	3.08
8	32.08	2.88	3.46	3.74	3.24	3.17	31.07	2.81	3.37	3.64	3.14	3.12
9	33.25	2.97	3.57	3.85	3.35	3.23	33.04	2.95	3.55	3.83	3.33	3.22
10	32.95	2.94	3.54	3.82	3.32	3.21	33.30	2.97	3.57	3.85	3.35	3.23
11	22.07	2.12	2.53	2.74	2.27	2.63	22.56	2.16	2.58	2.79	2.32	2.66
12	22.53	2.15	2.57	2.79	2.31	2.66	22.46	2.15	2.57	2.78	2.31	2.65
13	22.90	2.18	2.61	2.82	2.35	2.68	22.70	2.17	2.59	2.80	2.33	2.67
14	23.62	2.24	2.68	2.90	2.42	2.72	23.27	2.21	2.64	2.86	2.39	2.70
15	24.12	2.28	2.73	2.95	2.47	2.75	23.19	2.21	2.64	2.85	2.38	2.70
16	23.37	2.22	2.65	2.87	2.40	2.71	23.17	2.20	2.63	2.85	2.38	2.70
Mean	27.82	2.56	3.07	3.31	2.83	2.95	27.12	2.50	3.00	3.25	2.76	2.91
COV	14.53	11.99	12.26	12.12	13.82	7.37	14.12	11.60	11.87	11.73	13.42	7.08

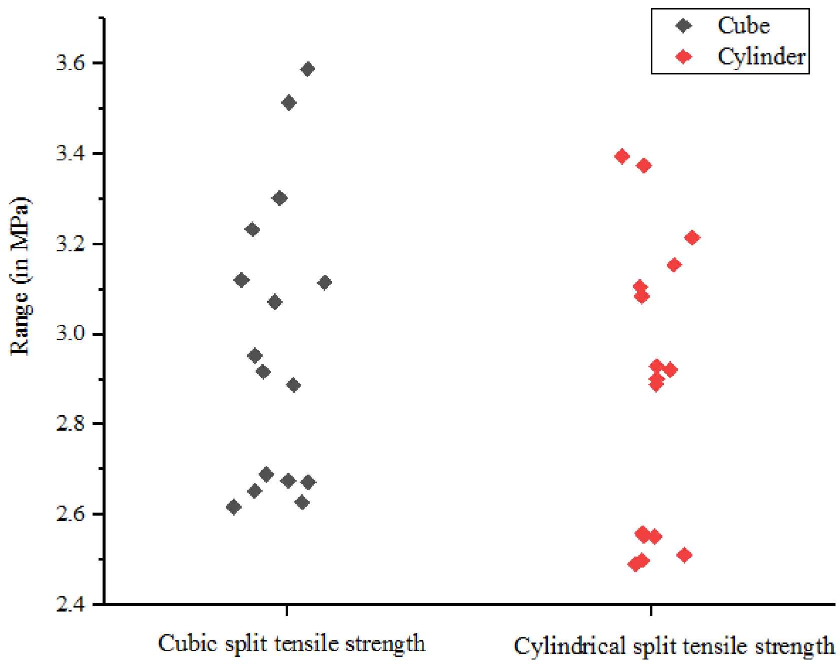


Fig. 2. Comparison of predicted cubic and cylinder split tensile strength.

Of the four prediction models considered in the present study for estimating the compressive strength, model Cp-2 (Metwally 2014) requires 28-days strength as an input value while the other three models rely on 7-days strength to predict strength beyond that age. The development of models Cp-3, Cp-4 (Masood and Murtaza 2015) gives weightage to the chemical compounds of cement by incorporating dimensionless factors such as α and β as they are the ones which are primarily responsible for rate of gain of strength by concrete. The model Cp-1 (Ahsanul et al. 2012) presents a mathematical expression with only one input strength value and using which two constants p and q are calculated. It is also reported that any day strength as high as strength at 365-days can also be calculated using this model. Hence, this prediction model can be conveniently used to assess the durability aspects of concrete structures where later-age strength development is of prime importance. Models Cp-3and Cp-4 mentions a certain limitation with respect to use of the models beyond the age of 28-days and informs the readers to carefully examine the constants α and β before using them for other types of cements.

Normally, splitting tensile strength of concrete is determined by testing cylindrical concrete specimens in the laboratories and hence most of the regression based models utilize the same component, f_c in their expressions. The reported model Tp-1 highlights the use of 28-days cubic compressive strength of concrete. It can be seen from Fig. 2 when predicted cubic of Tp-1 and predicted cylindrical split tensile strength of Tp-$2_{i,ii,iii,v}$ (Mehrdad and Ramezan 2021) and Tp-2_{iv} (Ramadoss 2014) are plotted on the same scale, the range of values obtained are similar. Hence, this model proves as an advantage in cases where only cube compressive strength data is available.

5. Conclusions

In recent times, it is observed that numerous types of prediction models are available in literature and some of them appear to be too complex to use it in any other circumstance because of involvement of complex variables and various constraints. In the present study, attempts are made to collate a few of the simple statistical based prediction models developed on normal concrete, with an objective to investigate the efficacies of these models as they are of great help to determine the two most important and governing design properties of structural elements, that is, compressive strength and tensile strength of concrete. Four types of prediction models for estimating compressive strength and two kinds of prediction models for assessing the tensile strength are dealt in this research article. Computations using the prediction models and subsequent comparison with experimental data shows that cube compressive strength is almost nearly equal to cylinder compressive strength wherein the latter is pronounced as more accurate type of measure in literature. The use of these non-expensive prediction models with an efficiency of 94% to 98% as obtained from the present study suggest a way to arrive at early and later-age compressive strength and split tensile strength of normal concretes without having to wait for long time to obtain results in the laboratory and can positively proceed to incorporate them in the design phase of structural members. In addition, this research work showcases that any age data, say 7-day strength data can be easily used on the cylinder-based suggested prediction models to predict the concrete compressive strength at any age and can also be used to obtain the split tensile strength of concrete. As the present study considers the use of suggested models for estimating the compressive and split tensile strength of normal concretes, efforts could be made to account the relation of flexural strength of concrete with these two leading parameters for an insightful and comprehensive understanding.

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Conflict of Interest

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