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ENGLISH VERSION...

Study on effect of marble powder and waste foundry sand as fine aggregates on the properties of metakaolin-cement concrete.

Estudio sobre el efecto del polvo de mármol y los residuos de arena de fundición como agregados finos en las propiedades del hormigón hecho con cemento de metacaolín.

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Abstract

To bring an challenging and acceptable change in construction industry, upcoming graduates have to be much aware of alternate materials to be used in conventional concrete with improved performances and this study can be an encouraging approach to them. Many research studies have investigated the possible use of industrial by-products such as fly ash from thermal power plants, red mud from aluminium manufacturing industry, copper slag from copper smelting industry, GGBS from steel industry, and waste foundry sand from metal casting industries in cement concrete production. Here, it is investigated on the possibility of utilizing two industrial by-products in the production of concrete for achieving sustainable development. Metakaolin is used for replacing a specific percentage of cement, and waste marble powder and waste foundry sand are used to replace different percentages of conventional fine aggregates (sand) for producing a sustainable concrete. It is observed from the results that properties of cement concrete are influenced by the percentage content of metakaolin, waste marble powder and waste foundry sand.

Keywords: *Metakaolin; Marble powder; Foundry sand.*

Resumen

Para generar un cambio desafiante y aceptable en la industria de la construcción, los futuros graduados deben conocer sobre que materiales alternativos se pueden utilizar en el concreto convencional mejorando su rendimiento, para ellos, este estudio puede resultar alentador. Muchos trabajos han investigado el posible uso de subproductos industriales como las cenizas volantes de las centrales térmicas, el lodo rojo de la industria manufacturera de aluminio, la escoria de cobre de la industria de fundición de cobre, los GGBS de la industria del acero y los residuos de arena de fundición de las industrias de fundición de metales para la producción de hormigón de cemento. Aquí se investiga la posibilidad de utilizar dos subproductos industriales en la producción de hormigón para lograr el desarrollo sostenible. El metacaolín se utiliza para sustituir un porcentaje específico de cemento, y el polvo de mármol residual y la arena de fundición residual se utilizan para sustituir diferentes porcentajes de áridos finos convencionales (arena) para producir un hormigón sostenible. De los resultados se observa que las propiedades del hormigón de cemento están influenciadas por el contenido porcentual de metacaolín, polvo de mármol residual y arena de fundición residual.

Palabras clave: Metacaolín; Polvo de mármol; Arena de fundición.

Highlights
- *M40 grade concrete is considered for sustainable development.*
- *Influence of metakaolin replaced for cement is studied.*
- *Effect of marble powder and waste foundry sand partially replaced for fine aggregate is studied.*
- *Mechanical properties, behaviour of reinforced member and resistance to acidic environment were studied.*
- *The properties of concrete are enhanced ultimately with varied percentages of industrial by-products.*
- *The predicted models obtained linear conformity with the experimental data.*

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1. Introduction

Construction of civil infrastructures like bridges, highways, flyovers and residential buildings requires large quantities of raw materials such as fine aggregates and coarse aggregates for the production of concrete. While natural resources are being depleted for obtaining the aggregates, they are also being depleted for obtaining the raw materials required for manufacturing cement. For achieving sustainability, construction industry has been using industrial by-products such as fly ash, ground granulated blast furnace slag (GGBS), silica fume, red mud, waste marble powder, waste foundry sand, rice husk ash, used rubber tyres, broken glasses, plastic wastes etc. as one of the ingredients in the production of cement concrete and mortar. Concrete consisting of one or more industrial by-products as replacement materials for cement or aggregates, thereby reducing the use of natural resources as fine and coarse aggregates, can be considered to be sustainable. Many research studies have already been conducted on the use of these by-products, some of them (in particular, use of fly ash and GGBS) have been put in practise also. Many studies are available in the literature that investigated the possibility of using metakaolin for replacing cement and waste marble powder or waste foundry sand for replacing aggregates. Research studies (Ramezanianpour and Jovein, 2012), (Dadsetan and Bai, 2017), (Hamdy K. et al., 2017), (El-Diadamony et al., 2018) are found reported in the literature that investigated the use of metakaolin as a replacement material for cement in the production of cement concrete. Different grades of metakaolin are available, and it has been reported that (Sabir et al., 2001), the mechanical properties and microstructural aspects of concrete depend on the grade of metakaolin. Test results have showed that it is possible to achieve strength comparable to that of control concrete even with the use of low-grade metakaolin. Addition of metakaolin in concrete for replacing cement alters the kinetics of the hydration and influences its microstructural characteristics (Zhao and Khoshnazar, 2020).

Results have also shown that metakaolin influences the hydration products and even changes the phase assemblages to look completely different from that of concrete produced with conventional cement. (Zˇeníšek et al., 2017) have observed that metakaolin positively influences the compressive strength and rheological properties of concrete. (Omar et al., 2012) have observed, through experimental investigations, that addition of waste marble sludge acted as filler in the pores of the concrete and improved its compressive strength at 15% of its use. It has been reported that, waste marble sludge could be used to replace conventional fine aggregates than for replacing cement. Because, utilization of waste marble sludge as replacement material for cement decreased the mechanical properties; however, when it was used for replacing conventional fine aggregates, it improved the mechanical properties (Aliabdo et al. 2014). (Mashaly et al., 2016) have found through experimental study that increase in use of waste marble content up to 20% increased the compressive strength of concrete; however, when the replacement level was more than 20%, the concrete strength decreased. (André et al., 2014) and (Gameiro et al., 2014) have observed that use of waste marble powder does not significantly influences its bulk density. However, test results showed that use of waste marble powder decreased the durability properties of concrete. With respect to use of waste foundry sand in the production of concrete, (Torres et al., 2017) have found that use of waste of foundry in concrete does not significantly influence its properties up to 30% of replacement of conventional fine aggregates.

(Siddique et al., 2018) have remarked that by using waste foundry sand in concrete have economic and environmental advantages. Slight improvement in the mechanical properties was observed by (Singh and Siddique, 2012) and (Siddique et al., 2015) when 30% of waste found sand was used for replacing fine aggregates. (Khatib et al., 2013) have found that strength of concrete decreased linearly with increase content of waste foundry sand. (Monosi et al., 2013) studied the use of two different types of waste foundry sand in concrete, and observed that the waste foundry sand could be used in mortar and concrete to be used for structural applications. The current status of utilization of industrial by-products for using as raw materials for the manufacturing of some other products is discussed in this section based on the brainstorming session report (IIT Bombay report, 2018). These observations clearly indicate that, even though studies are being carried out in various academic and research institutions of the country on the feasibility of using industrial by-products in various civil engineering projects, utilization of the industrial by-products has not become practical in every construction projects. Earlier (Sakthieswaran and Priyanka, 2019), the investigations observed for the properties of metakaolin, foundry sand and marble powder and workability and mechanical and durability properties of cement concrete with the sustainable concrete developed. Microstructure properties also observed using X-Ray Diffractometer analysis and Scanning Electron Microscope. Here, it is proposed to experimentally investigate the properties of bonding with steel resistance to acid attack and sorptivity. It is also investigated here the flexural property of structural member made with concrete consisting of metakaolin, waste marble sand and waste foundry sand.

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2. Materials

Ordinary Portland Cement of 43 grade conforming to IS8112 is used in this investigation observed for specific gravity of 3.15, initial and final setting time of 39mins and 220mins repectively. Metakaolin has particle size between the range as that of cement and silica fume. The properties of metakaolin used here comprises off-white colour, powder form and specific gravity of 2.6. Metakaolin is used for replacing binder conforming to recommendations by BIS documented CED 2(7921).

River sand of grade Zone III conforming to IS2386(1) is used for this investigation. The fineness modulus and specific gravity of the natural river sand used in this investigation are 2.49 and 2.85 respectively. Waste foundry sand extracted as waste from foundries are collected in the nearby moulding Industry. The specific gravity and fineness modulus of used foundry sand is 2.62 and 2.68 respectively. Marble powder ready for dumping is used in this study and are supplied by local cutting and tiling units. The properties observed for marble powder similar to foundry sand. Coarse aggregate of specific gravity 2.71 and fineness modulus of 7.85 also satisfying the recommendations conforming to IS2386(1) is used throughout the study. Local potable domestically supplied water conforming to acceptable pH, turbidity and hardness levels is used for this investigation. Mix is designed for reducing 20% water with addition super plasticizer Conplast 420 of specific gravity 1.185.

3. Methodology

Design mix of M40 grade concrete with w/b ratio 0.4 is attained for its target values as per the procedure in IS10262.The mix proportion for the desired control concrete is as shown in (Table 1). From the literature study made closer to the replacement levels of fine aggregate by waste foundries and marble powder, it is investigated with the following proportion level. It will be easier to investigate the mechanism on amount of replacement for binder as well fines by metakaolin, waste foundry sand and marble powder respectively.

The proportion of reusable waste materials is represented by weight of binder and fines shown in (Table 2).

Table 1. *Mix Design and Proportion*

Design Mix	Water	Cement	Fine Aggregate	Coarse Aggregate
By Volume (kg/m^3)	164	350	729	1250
By ratio	0.4	1	2.08	3.57

Table 2. *Replacement percentage for binder and fine aggregate*

Mix ID	Binder		Fine Aggregate		
	Cement	Metakaolin	Sand	Marble powder	Waste Foundry sand
	%	%	%	%	%
M0	100	0	100	0	0
M1	95	5	90	5	5
M2	95	5	80	10	10
M3	95	5	70	15	15
M4	95	5	60	20	20

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Bond strength of the concrete specimens was tested by carrying out tensile testing on the rebar embedded in concrete cube specimens that are restrain from moving. The bond strength was carried out as per the recommendations given in IS 2770(1)-1967. Determination of bond strength consisted of cleaning of the specimens after curing period.

Placing the specimen along with the rebar clipped to the moving ram. Placing of dial gauges for measuring the slip of the embedded rebar. Loading applied at a rate of 2250 kg/min till failure. The bond strength of the concrete was determined using $fp = P / (\pi DLe)$*, where, P – Load (N), Le – Length of rod embedded (mm), D – Diameter of bar (mm). Sorptivity of the concrete specimens was determined as per the recommendations of ASTM C1585. Cylindrical specimens of diameter 100 mm and height 50 mm were considered for the study. Determination of sorptivity of the concrete specimens consisted of casting and curing of the specimens. Sealing the side surfaces with insulating material. Determination of initial weight of the specimens. Determination of weight of the specimen for every five min after exposing one surface to the water. Calculating sorptivity coefficient using the formula* $S = \{(\Delta M \sqrt{t})\}/\{AXd\}$ *where, S = Sorptivity in mm/√s, ΔM= change in specimen mass in grams over a time interval, A = the exposed area of the specimen in cm2, d = density of the water in g/cc. The resistance of the sustainable concrete mixes to attack of acids such as sulphuric acid and hydrochloric acid was determined by calculating the mass loss of the specimens after subjecting them to acid attack. The test was carried out as per the recommendations given in IS 516-1999. Concrete cube specimens of size 150 x 150 x 150 mm were considered. The testing consisted of cleaning of the concrete cube specimens after curing period. Determination of mass of the specimens after curing. Preparation of acid solutions. Immersion of the specimens in the acid solutions for a specific period of time. Determination of the mass of the specimens after exposure period. Determination of mass loss of the specimens is calculated by ratio of the change in weight before and after exposure and initial weight before immersion. The flexure behaviour of reinforced concrete beams cast with the sustainable concrete mixes was determined under four-point bending. The dimension of the beam specimens considered was 2910 mm x 150mm x 300mm (length x width x depth). The beam specimens were cast and cured by immersion in water. For all the beam specimens, one edge was simply supported and the other edge was supported on the roller. The flexural loading was applied using a hydraulic jack of capacity 500 kN at a loading rate of 5 kN/min. The deflection of the beam specimens at mid-span was monitored using Linear Variable Differential Transducer (LVDT) till failure of the specimens.*

4. Result and Discussions

Earlier the proposed concrete mixes were investigated for its fresh and hardened properties at various curing ages and presented (Sakthieswaran and Priyanka,2019). From that, it is reviewed here together and evident as follows; The workability of the concrete was very much influenced due to the addition of waste foundry sand and marble powder. The relative decrease in the workability was achieved due to the increase in amount of water required by the aggregates and the normal sand. The flexural strength of the concrete mixes was also enhanced due to the fine aggregate replacement. The impact strength of the concrete was also much enhanced for the concrete containing metakaolin as cement replacement and marble powder and waste foundry sand as fine aggregate replacement that proved to be efficient in absorbing the impact energy acting on the concrete. The water absorption of the concrete mixes was also much reduced due to the fine aggregate replacement by waste foundry sand and marble powder. The addition of metakaolin also reduced the water absorption due to their filler effect. The reduction in the water absorption caused a decrease in the voids and is responsible for the improvement in the mechanical strength and impermeability properties of concrete. The addition of metakaolin caused stronger bonding of the cement paste and strengthens the adherence of the cement and the aggregates by the formation of CSH gel which is also responsible for the reduction in the porosity values. The X-ray diffraction studies also showed the minimal presence of calcium hydroxide that confirmed the consumption of calcium hydroxide in the hydration reaction which is responsible for the dense microstructure of the concrete by the addition of CSH gel. The reduced calcium hydroxide peaks inherits the formation of CSH gel that is responsible for the improved strength and durability of the concrete. The SEM images of the concrete also showed reduction in the voids in the concrete and the well distributed CSH gel that effectively bonded the fine aggregates with the cement matrix. The SEM micrographs also showed the good correlation between the obtained mechanical properties and the morphology of concrete mix and shows that the marble powder and waste foundry sand in combination with metakaolin can be used for making good quality concrete with higher strength. The extended investigation about the effect of metakaolin, marble powder and foundry sand on bond strength, reinforced member, capillary action and resistance to sulphuric and hydrochloric acid is discussed below.

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4.1. Bond Strength

When the specimen is subjected to loading with bars gripped onto the jaws, the bar is observed to be strong in tension whereas concrete is strong in compression. The bar is slipped at particular stage of load and causes splitting failure cracks on the concrete in which the bar is embedded. The results shows that increase in replacement of fines increase the bond strength between steel and concrete.

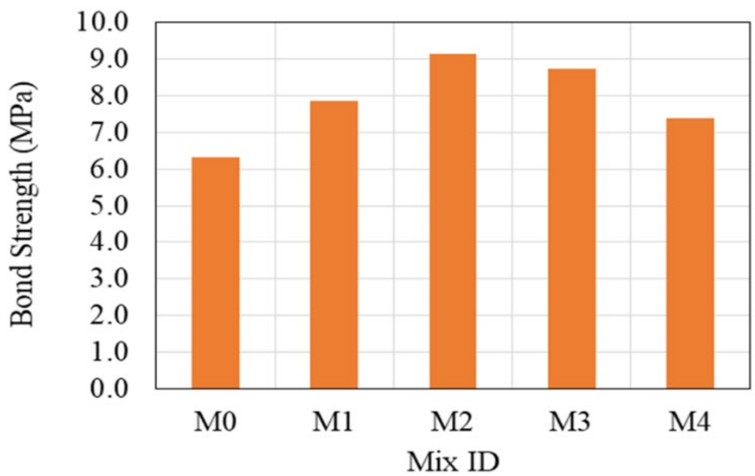

Figure 1. *Variation of Bond Strength of Mixes*

In general, it was observed from the test results (Figure 1) that variation of bond strength of the mixes considered followed similar trend of compressive strength variation. The effect of addition of metakaolin, marble powder and waste foundry sand on the bond strength of concrete could be determined from bond strength ratios calculated as the bond strength of the mixes (M1, M2, M3 and M4) with respect to control concrete mix (M0). The bond strength ratios are given in (Table 3).

Table 3. *Variation of Bond Strength of Mixes*

S. No.	Mix ID	Bond Strength Ratio
1	M0	1.00
2	M1	1.25
3	M2	1.45
4	M3	1.39
5	M4	1.17

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It was observed from (Figure 1) and (Table 3) that bond strength of the mix M2 was more than the other mixes. Presence of metakaolin and increase in the percentage use of marble powder and waste foundry sand up to a specific percentage (5%) increased the bond strength of the mixes. As the percentage use of marble powder and waste foundry sand was increased beyond 5%, the bond strength decreased; however, it was observed that even with increased percentage (10 and 15%) use of marble powder and waste foundry sand, the bond strength of the mixes (M3 and M4) was more than the control mix. In general, test results showed that the bond strength of all the mixes considered was more than the control concrete mix.

4.2. Sorptivity

The water absorption by capillary action of the concrete mixes considered is shown graphically in (Figure 2).

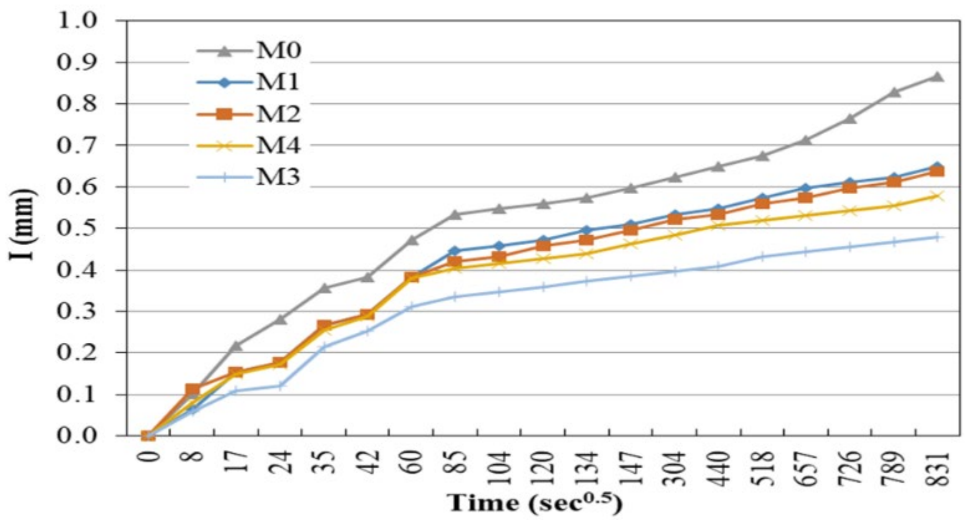

Figure 2. *Sorptivity Test Results*

It was observed from (Figure 2) that the water absorption by capillary action was more for the control mix (M0) as compared to other concrete mixes (M1, M2, M3 and M4). The water absorption was found to be the least for the concrete mix M3. Test results (Figure 2) showed that water absorption by capillary action was lesser for the concrete mix (M3) that achieved higher compressive strength. The reason for this could be due to decreased porosity of the concrete mix M3 as compared to the other concrete mixes considered in the experimental program.

4.3 Resistance to acid attack

4.3.1 Hydrochloric Acid

The percentage loss in weight of the concrete cube specimens subjected to hydrochloric acid attack is given graphically in (Figure 3). It was observed from (Figure 3) that, in general, the percentage of mass loss was more for the control concrete mix (M0) as compared to the other concrete mixes (M1, M2, M3 and M4). It was observed from the test results that (Figure 3), addition of metakaolin and increase in the percentage use of marble powder and waste foundry sand decreased the percentage loss in mass of the concrete mixes considered.

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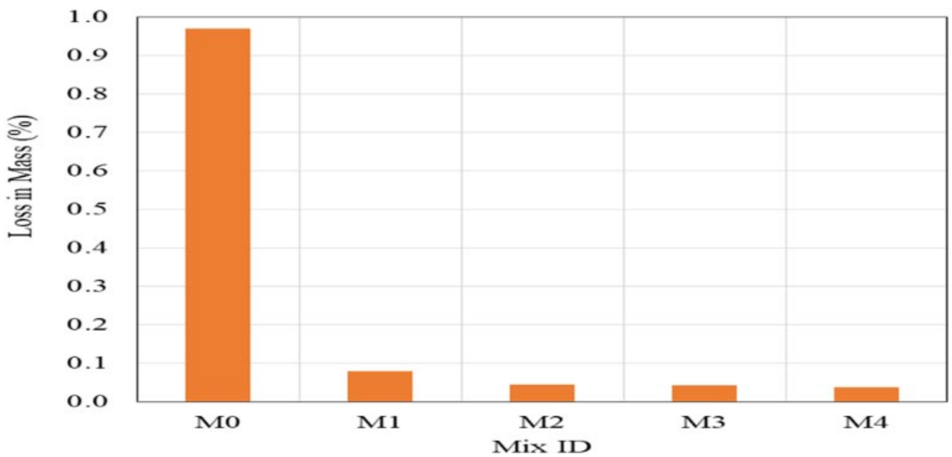

Figure 3. *Variation of Percentage of Mass Loss*

Marble powder and waste foundry can be considered to be inert as compared to the cementitious materials such as cement and metakaolin. Therefore, the reduced loss is mass in the mixes M1, M2, M3 and M4 could be primarily due to the presence of marble powder and waste foundry sand. It is also important to note that waste foundry sand would have already been subjected to very high temperature during metal casting process and would relatively achieved a stable state. With increased use of marble powder and waste foundry sand, there would be less cementitious materials whose chemical compounds after hydration reaction are likely to change its characteristics after subjecting to acid attack. These observations indicate that the reduced percentage loss in mass of the mixes M1, M2, M3 and M4 is due to the increased content of inert materials (or fillers) such as marble powder and waste foundry sand. The percentage loss in compressive strength of the concrete mixes after subjecting to hydrochloric acid is pictorially represented in (Figure 4).

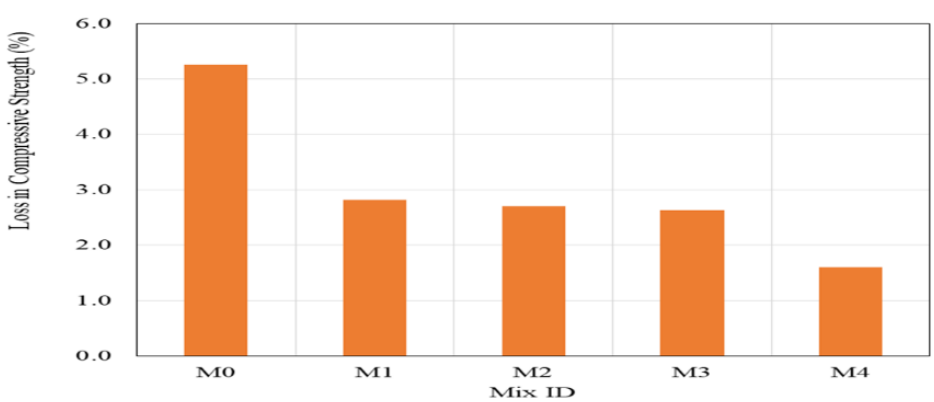

Figure 4. *Variation of Percentage Loss in Compressive Strength*

4.3.2 Sulphuric Acid (H_2SO_4)

The percentage loss in weight of the concrete cube specimens subjected to sulphuric acid attack is represented graphically in (Figure 5). It was observed from (Figure 5) that the percentage loss in mass of the concrete mixes decreased with increase in the percentage use of marble powder and waste foundry sand. The trend of decrease in the percentage loss in mass was found to be similar to the specimens subjected to hydrochloric acid attack, and the reasons stated earlier is equally applicable for the specimens subjected to sulphuric acid attack also. However, it was found that the percentage loss in mass was more in the concrete specimens subjected to sulphuric acid attack as compared to that of hydrochloric acid attack.

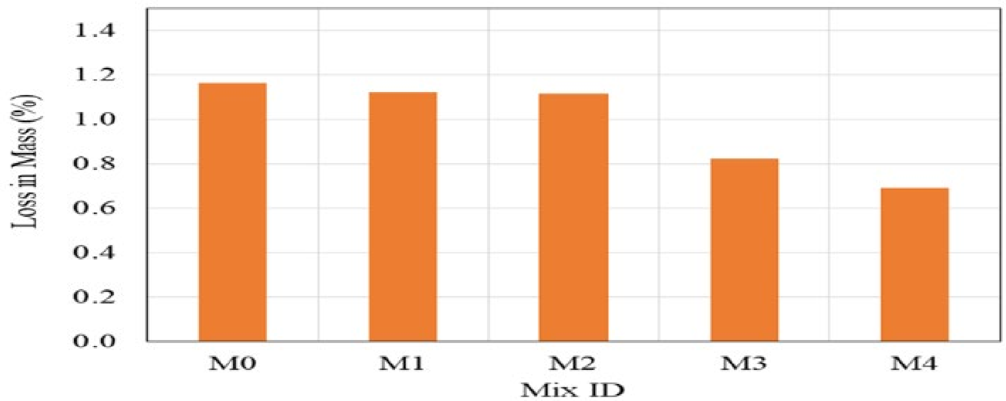

Figure 5. *Variation of Percentage of Mass Loss*

The percentage loss in compressive strength of the concrete specimens subjected to sulphuric acid is represented graphically in (Figure 6).

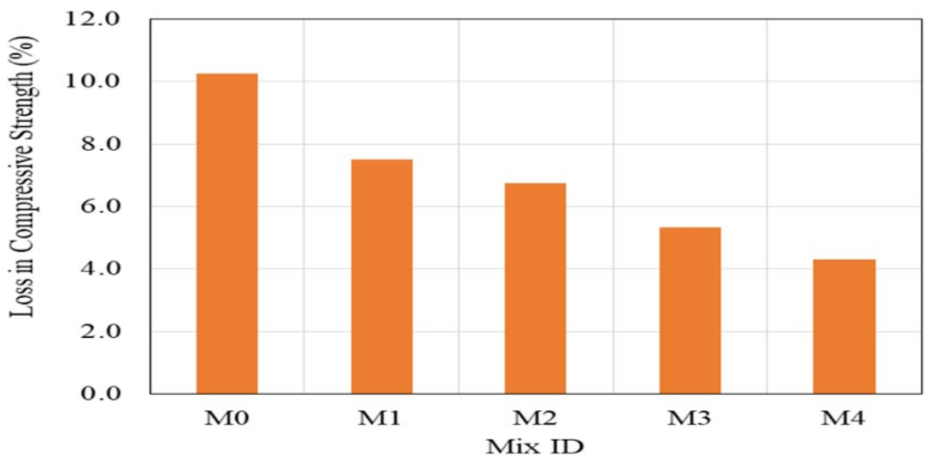

Figure 6. *Variation of Percentage of Compressive Strength Loss*

It was observed from (Figure 6) that percentage loss in compressive strength of the concrete specimens subjected to sulphuric acid attack decreased with increase in the percentage use of marble powder and waste foundry sand. This observation was found to be similar to that in the specimens subjected to hydrochloric acid attack; however, the percentage loss in compressive strength was more in the specimens subjected to sulphuric acid attack.

4.4 Flexural behaviour of concrete beams

The results of the flexural testing of concrete beams cast with the concrete mixes considered are presented in this section. The first crack load and ultimate load of the tested beams and the deflection corresponding to these loads are given in (Table 4).

Table 4. *Flexural Test Results*

S. No.	Mix ID	First Crack Load (kN)	Deflection at First Crack (mm)	Ultimate Load (kN)	Deflection at Ultimate load (mm)
1	M0	37.5	2.3	73.0	5.5
2	M1	51.0	2.2	83.5	4.1
3	M2	65.5	3.0	93.5	5.1
4	M3	62.5	3.0	92.0	6.6
5	M4	49.5	2.1	82.5	4.0

It was observed from (Table 4) that the first crack load of the tested beams was influenced by the concrete mixes considered. The first crack load of the sustainable mixes M1, M2, M3 and M4 was observed to be more than that of the control concrete mix M0.

Test results showed that the first crack load of the sustainable concrete mixes M1, M2, M3 and M4 increased with increase in the percentage use of marble powder and waste foundry sand up to a 10% percentage beyond which the first crack load decreased.

Even though increase in the percentage use of marble powder and waste foundry sand beyond 10% in the mixes M3 and M4 decreased the first crack load, it was observed that it was more than that of control concrete beam. The beam with concrete mix M2 achieved higher first crack load as compared to all other mixes considered. The reason for this observation could be attributed due to higher flexural and spitting tensile strength of the concrete mix M2. The load vs. deflection curves of the tested beams are shown in (Figure 7).

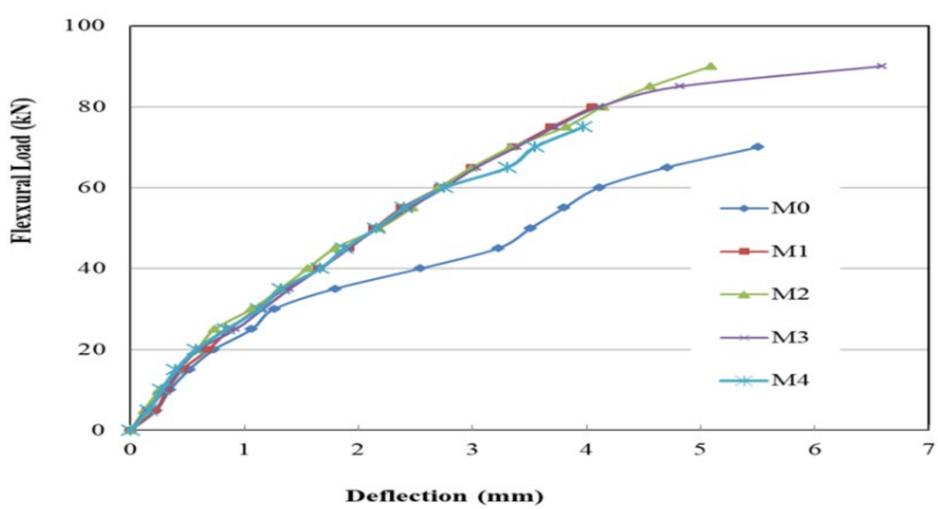

Figure 7. *Load-Deflection Curves*

Table 5. *Flexural Toughness of the Beams*

S. No.	Mix ID	Flexural Toughness (kNmm)
1	M0	37.5
2	M1	51.0
3	M2	65.5
4	M3	62.5
5	M4	49.5

It was observed from (Figure 7) increase in the applied flexural loading increased the lateral deflection of the beams. Test results (Figure 7) showed that, for a specific applied flexural load, the deflection achieved by the control concrete beam (M0) was found to be more than that of other beams cast with sustainable concrete mixes M1, M2, M3 and M4. This observation indicated that the energy absorption capacity of the concrete beams cast with sustainable concrete mixes was more than that of the control concrete beam. The flexural toughness of the tested concrete beams was calculated (corresponding to 2.5mm deflection) as the area under the load vs. deflection curves of the beams and is given in (Table 5).

It was observed from (Table 5) that the flexural toughness of the tested beams was influenced by the presence of metakaolin, marble powder and waste foundry sand. The flexural toughness of the concrete beam cast with mix M2 was found to be more than all the beams considered. Also, test results (Table 5) showed that the flexural toughness of the beams cast with sustainable concrete mixes M1, M2, M3 and M4 was found to be 27% more than the control concrete beam cast with the mix M0.

4.5 Regression Analysis

From the experimental data, graphs were plotted between 28 days flexural strength (Sakthieswaran and Priyanka, 2019), and bond strength of concrete mixes. The linear relationship between flexural strength and 28 days bond strength is obtained through the predicted equation y= 1.1102 x – 0.9522 and their corresponding regression coefficient R2= 0.9677 as shown in (Figure 8).

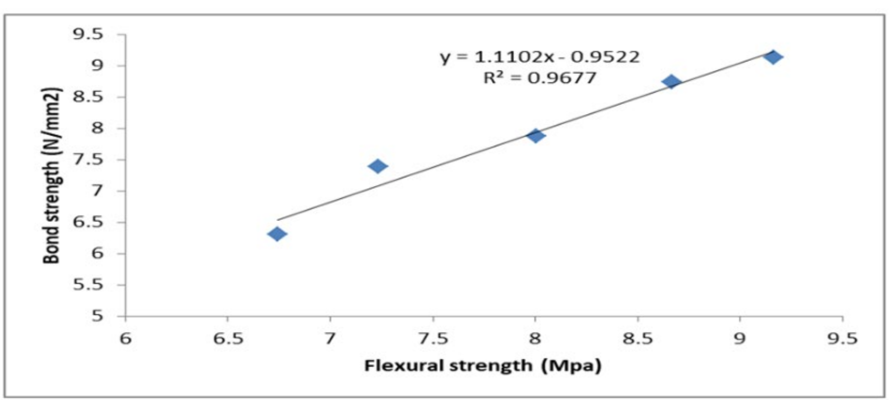

Figure 8. *Relation between flexural strength and Bond strength*

The linear relationship between split tensile strength and 28 days bond strength is obtained through the predicted equation y= 3.7351 x – 9.7869 and their corresponding regression coefficient R2= 0.9242 as shown in (Figure 9).

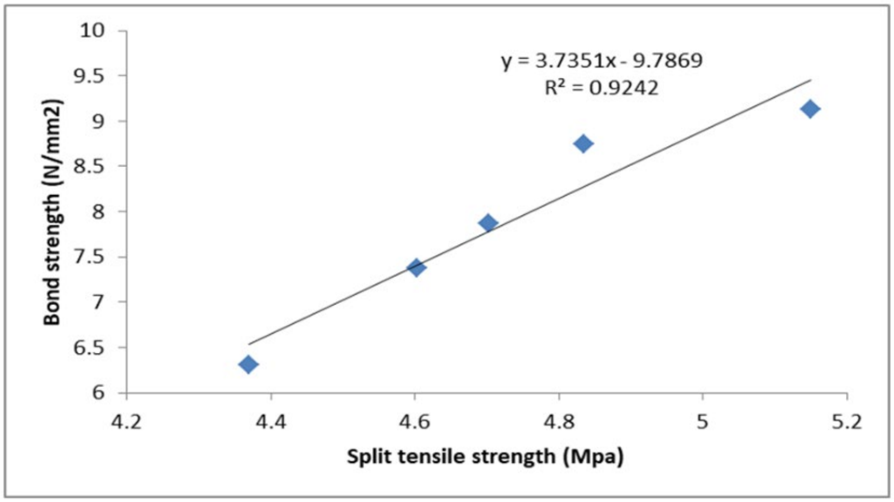

***Figure 9.** Relation between split tensile strength and Bond strength*

The linear relationship between water absorption and sorptivity at 15 mins is obtained through the predicted equation y = 0.001 x – 0.038 and their corresponding regression coefficient R2 = 0.9062 as shown in (Figure 10).

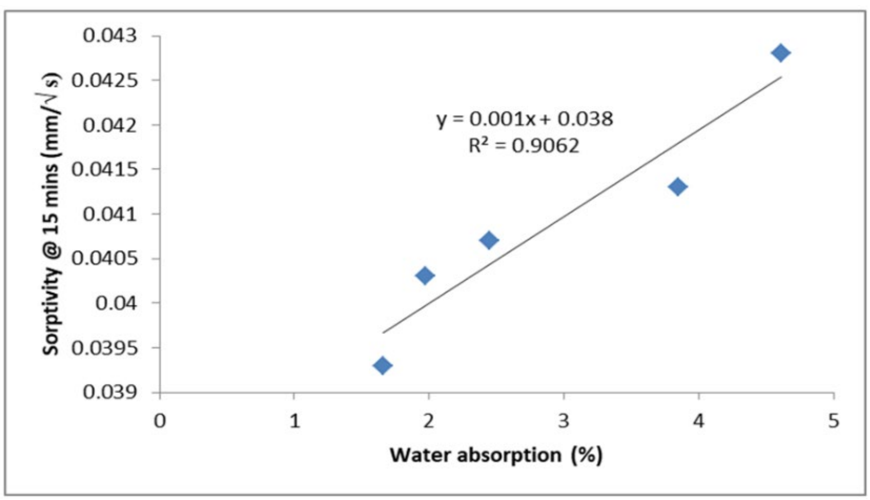

***Figure 10.** Relation between water absorption and Sorptivity at 15 mins*

The linear relationship between water absorption (Sakthieswaran and Priyanka, 2019) and sorptivity at 30 mins is obtained through the predicted equation y= 0.0014 x – 0.0254 and their corresponding regression coefficient R2= 0.8755 as shown in (Figure 11).

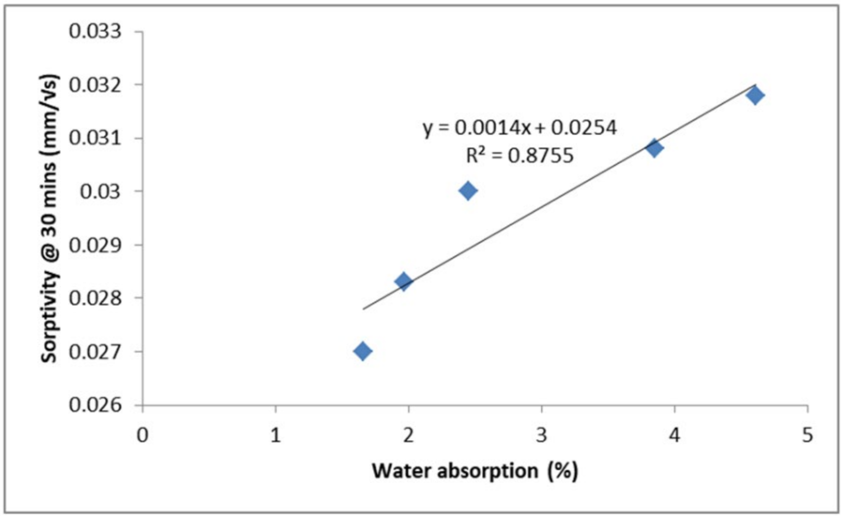

Figure 11. *Relation between water absorption and Sorptivity at 30 mins*

From the experimental data, graphs were plotted between sorptivity at 15 mins and 28 days loss in weight due to HCL attack of various concrete mixes. The linear relationship between sorptivity at 15 mins and loss in weight due to HCL attack is obtained througt the predicted equation y = 267.17 x – 10.687 and their corresponding regression coefficient R2= 0.7101 as shown in (Figure 12).

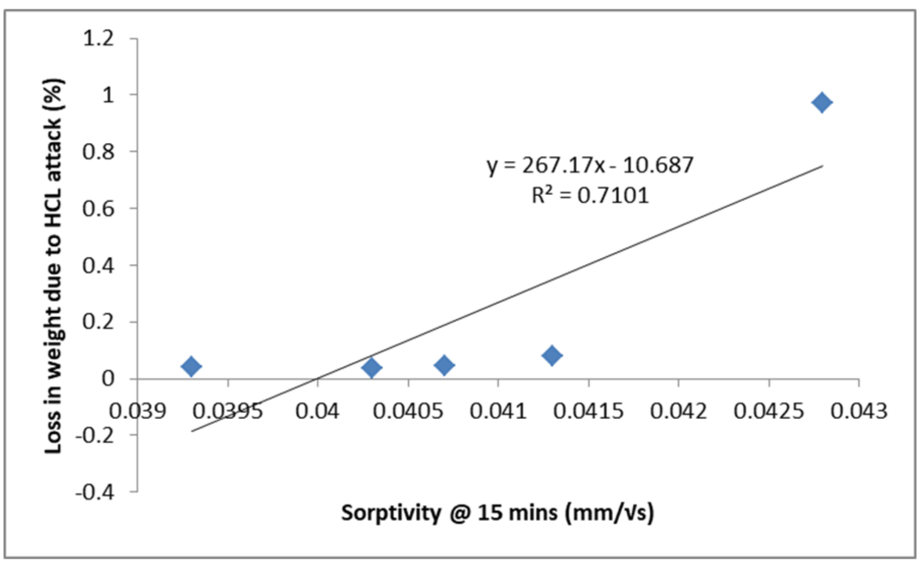

Figure 12. *Relation between Sorptivity at 15 mins and loss in weight due to HCL attack*

The linear relationship between Sorptivity at 30 mins and loss in weight due to H2SO4 attack is obtained through the predicted equation y = 95.281x - 1.835 and their corresponding regression coefficient R2= 0.7432 as shown in (Figure 13).

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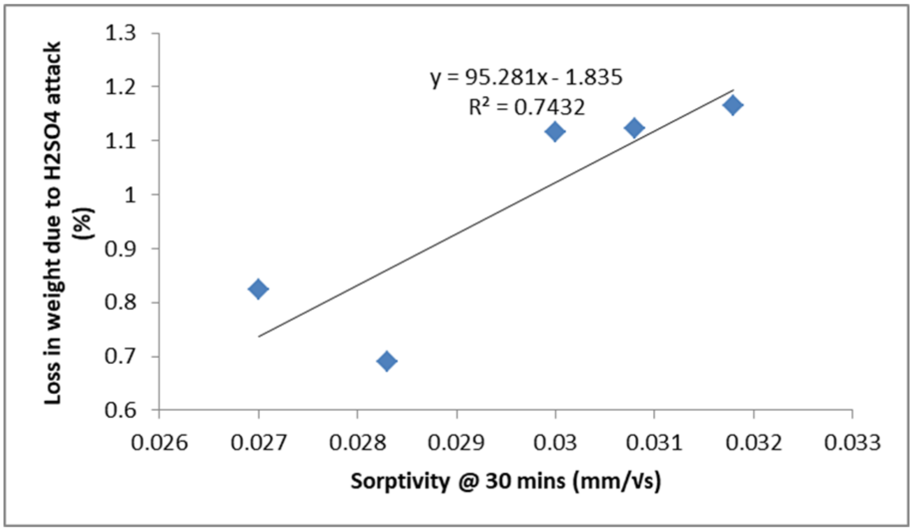

Figure 13. *Relation between Sorptivity at 15 mins and loss in weight due to HCL attack*

The linear relationship between Sorptivity at 15 mins and loss in strength due to H2SO4 attack is obtained through the predicted equation y = 1588.6x - 58.111and their corresponding regression coefficient R2= 0.8202 as shown in (Figure 14).

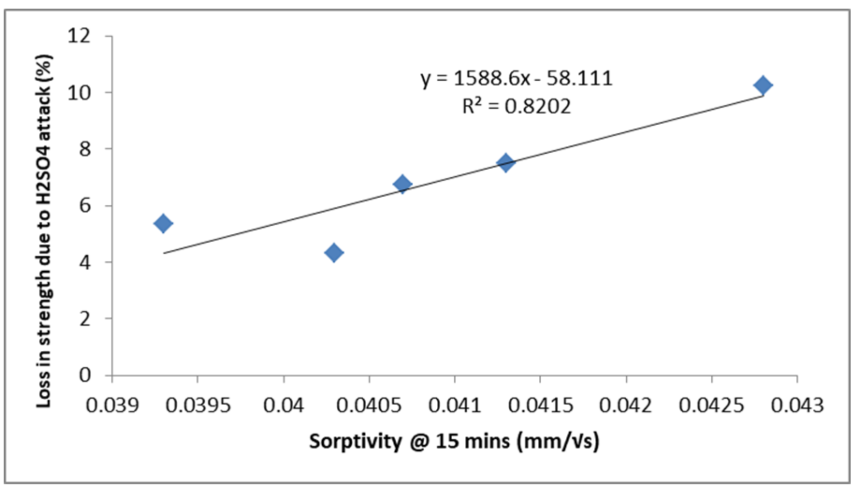

Figure 14. *Relation between Sorptivity at 15 mins and loss in weight due to HCL attack*

The linear relationship between Sorptivity at 30 mins and loss in strength due to H2SO4 attack is obtained through the predicted equation y = 1038.4x - 23.884 and their corresponding regression coefficient R2= 0.7754 as shown in (Figure 15).

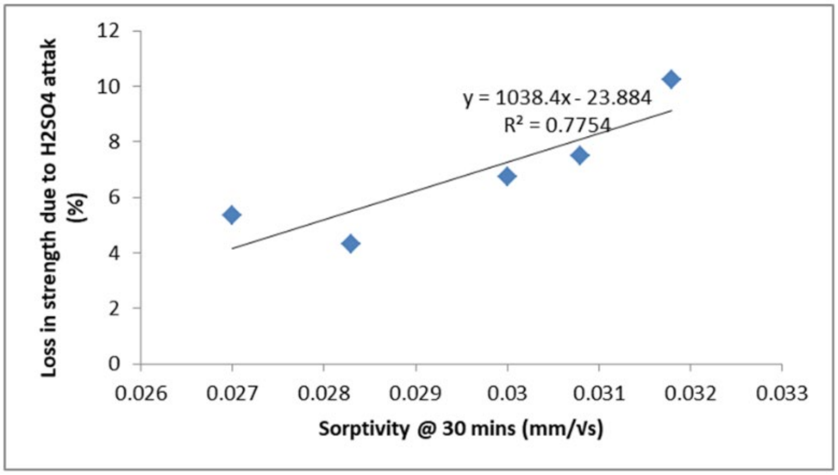

Figure 15. *Relation between Sorptivity at 30 mins and loss in strength due to H_2SO_4 attack*

5. Conclusions

From this investigation, it is concluded that use of clay kaolin, foundrysand and marble powder is studied for its effective utilization in concrete industry. This could definitely be the trigger key to the graduating readers to achieve great peaks in construction industry. The observance and summarized recommendations are presented here. Interpretating with earlier and present investigations, the Workability of the proposed sustainable concrete mixes decreased due to the presence of metakaolin, marble powder and waste foundry sand. Superplasticizer is necessary to achieve the required workability of the sustainable concrete mixes. The sustainable concrete mix consisting of 5% metakaolin for replacing cement, and 15% of marble powder and 15% of waste foundry sand for replacing conventional fine aggregates achieved higher compressive strength as compared to other mixes considered. The flexural strength and splitting tensile strength of the concrete mix consisting of 5% metakaolin for replacing cement, and 10% of marble powder and 10% of waste foundry sand for replacing conventional fine aggregates was higher than that of other mixes considered. The bond strength of the concrete also improved response when metakaolin used as partial cement replacement and marble powder and foundry sand used as partial replacement for fine aggregate. The bond strength mainly depends on the density of the concrete. The addition of metakaolin also improved the shear strength of the concrete which ultimately increases the bond strength of the concrete. Resistance to acid attack of the sustainable concrete mixes increased with increase in the percentage use of marble powder and waste foundry sand. The refinement of the pore structure of the concrete by using metakaolin and the better spread up CSH gel formation reduced the permeability of the concrete by improved resistance to aggressive environment. The prediction models obtained from the experimental data showed the relationship between various strength parameters of the concrete and the obtained R2 values indicate the conformity of the interrelationship between the variables and relationship can be considered to be linear up to 15 % use of marble powder and waste foundry sand.

6. Referencias

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