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CHAPTER 1
INTRODUCTION

1.1 Excessive Sand Mining and its Environmental Impacts:

Concrete, the single most widely used building material around the globe, is a heterogeneous composite that consists of combination of readily available basic building materials including cement, water, coarse aggregate, fine aggregate, and in some cases, admixtures, fibres or other additives, according to the need. When these ingredients are mixed together, they form a fluid mass that is easily moulded into any shape. Over time, when it is cured sufficiently, the cement forms a hard matrix which binds the rest of the ingredients together into a durable stone-like material, called concrete.

The reason behind the enormous use of concrete in the construction sector lies in its versatile, reliable and sustainable nature, because of its strength, rigidity, durability, mould-ability, efficiency and economy.

Humans have been using concrete in their pioneering architectural feats for millennia. Due to the ongoing boom in the housing sector and other developmental activities in the construction field, the demand of concrete is increasing with a very rapid pace all over the world. Worldwide, some 12 billion tons of concrete is being produced each year, as per a report published by United Nations Environment Program. Such volumes require vast amount of natural resources for aggregate and cement production. For instance, cement consumption around the world has multiplied three-fold in last 20 years, from 1.37 billion tons of cement in 1994 to 3.7 billion tons in 2012, mainly due to the rapid economic growth in Asia. Interestingly, China consumed about 58% of the total cement production in 2012.

The fine aggregate and coarse aggregates generally occupy 60% to 75% of the concrete volume and therefore, strongly influence the concrete's freshly mixed and hardened properties, mixture proportions, and economy. It is therefore, important to obtain right type and good quality aggregate at site, because the aggregate form the main matrix of concrete. Crushed stone and gravel are most commonly used as a coarse aggregate in concrete, while natural sand or river sand as a fine aggregate in concrete.

River sand is naturally occurring granular material composed of finely divided rock and mineral particles. River sand has the ability to replenish itself. The composition of sand is highly variable, depending upon the local rock sources and conditions, but the most common constituent of sand is silica (silicon dioxide), usually in the form of quartz, which because of its chemical inertness and considerable hardness, is the most common mineral resistant to weathering. Sand in the river channel and floodplains constitutes an important raw material in the construction industry and has a variety of uses in this sector.

These raw materials of concrete, i.e., river sand and gravel, are also struggling to cope with the rapidly growing demand in many areas around the globe. The sources of good quality river sand and gravel are depleting very fast. According to United Nations Environment Program (UNEP) report, “Sand-rarer than one thinks”, published in March-2014, sand and gravel has now become the most widely used natural resource on the planet after water. These are now being extracted at a rate far greater than their renewal.

Globally, between 47 to 59 billion tonnes of material mined every year, of which sand and gravel account for the largest share from 68% to 85%. The use of aggregates for concrete all over the world can be estimated at 25.9 billion to 29.6 billion tons a year for 2012 alone. Including the aggregate used in asphalt as well as concrete pavements and other industrial uses, this estimate can go up to 40 billion tons a year. This large quantity of material cannot be extracted and used without a significant impact on the environment.

Sand mining is an activity referring to the process of removal of sand from the foreshore including rivers, streams and lakes. Sand is also mined from beaches and inland dunes and dredged from large scale removal of riverbed materials and dredging below the streambed alters the channel form and shape, that, in turn, has several consequences such as erosion of the riverbed and banks, increase in channel bed slope and changes in channel morphology. Removed sand is a direct loss to the river system. It causes deepening of rivers and estuaries and it also enlarges river mouths and coastal inlets, which may also lead to the saline-water intrusion from the nearby sea. It is also a threat to bridges, river banks and other nearby structures.

In-stream sand mining activities degrade the quality of river water. The short term turbidity is increased at the mining site due to re-suspension of sediments and organic particulate matter. Oil spills and leakages from mining machinery and vehicles further aggravate the issue. Increase in suspended particles directly affect the water users by significantly increasing the water treatment costs and undermine the aquatic ecosystems. Sand removal turns riverbeds into large and deep pits which lowers the groundwater level in the wells of nearby areas, thus adversely affecting the local groundwater availability.

The stability of sand and gravel bed depends upon a delicate balance of the stream flow, sedimentation and channel form. Native species in streams are uniquely adapted to the stable bed structure. Unstable stream channels are inhospitable to most of the aquatic species.

Bed degradation and sedimentation have negative impact on aquatic life, disturbing the species attached to streambed deposits, leading to loss of biodiversity. Degraded stream habitats also result in loss of fishery productivity.

Physical disturbances due to human activities also lead to interruption in nesting/breeding activities. For example, in the National Chambal Sanctuary, mining of sand adversely affected ghariyals, who use sand banks for nesting and basking. They lay eggs under the sand beds, which were destroyed by sand mining related activities. The problem of environmental impacts associated with excessive sand mining has now become so serious that existence of river ecosystems is threatened in a number of locations, damage being more severe in small river catchment. As a result, many governments all over the world have banned sand mining from the rivers.

1.2 Alternatives for Natural Sand:

As the supplies of suitable natural sand near the point of consumption are becoming exhausted, the cost of this sand is increasing, which is ultimately increasing the cost of the construction. The demand of sustainable growth of infrastructure in modern times is to find an alternative material that should not only satisfy the technical specification of fine aggregate, but it should also be abundantly available. A lot of research has been done in the past to find alternate source of fine aggregate.

Crushed sands, fine aggregate produced from stone crushing, has become very popular in areas where natural sand is not abundantly available or where there is scarcity in the supply of natural sand. The Mumbai-Pune express highway was a project, where there is a difficulty in procurement of natural sand. This made the construction company to use crushed sand for making approximately 20 lakh cum of concrete necessary for the construction. However, such type of sands contains a large amount of micro-fines, i.e., particles finer than 75 microns, which can have an adverse effect on properties of concrete. So proportioning of different raw materials at the time of mix design is very important, when crushed sand is used in concrete.

Now a day, with ongoing research and development in this field, fine aggregate with the desired properties are manufactured by stone crushing. Manufactured sand can be defined as a purpose made crushed fine aggregate produced from a suitable source material. Its production generally involves crushing, screening and possibly washing, separation into discrete fractions, recombining and blending may be necessary. Manufactured sand is proving to be very beneficial in the areas, where natural sand is not available, or where there is a scarcity in the supply of natural sand. The introduction of better crushers tends to give better shaped crushed fine aggregate.

It must be kept in mind that crushed sand and manufactured sand are made by stone or rock crushing, which are also a natural resource like river sand. So increase in the use of crushed sand and manufactured sand may also lead to excessive mining of stones and rocks, which we are already using as coarse aggregates in concrete. This will be the start of new kind of environmental problems in the long run. So it is time to take a different approach on this issue.

Use of industrial by-products in concrete has drawn a serious attention of researchers and investigators in recent years. There are many waste materials of some industries that have been successfully used as a partial as well as full replacement of natural fine aggregate. Siddique Rafat (2014) gave an overview about the utilization of waste foundry sand, coal bottom ash, cement kiln dust and wood ash as partial replacement of natural sand on fresh, mechanical and durability properties of concrete and also discussed physical, chemical and mineralogical properties of each waste product. Dash et. al. (2016) also published a review article about the utilization of various industrial waste products and by-products as a replacement of fine aggregate such as waste foundry sand, blast furnace slag, steel slag, copper slag, imperial smelting furnace slag, coal bottom ash, ferrochrome slag, palm oil clinker etc. Each waste product has its specific effect on properties of fresh and hardened concrete. Such efforts are the need of the time, because it will not only save the disposal cost of such waste products, but also help in keeping our environment green and clean. Moreover, the use of industrial by-products in concrete help us to make a concrete with similar or improved fresh, mechanical and durability properties as compared to conventional concrete and also make our concrete more economical. Quarry dust is one of such by-products of stone crushing and processing industry, which has a great potential to be used as a partial replacement of river sand in concrete.

1.3 Quarry Dust:

Quarry dust can be defined as residue, tailing or waste material, left after the extraction and processing of rocks at crushing plant at a quarry. It is also known as stone dust, quarry waste or rock dust. When rock is crushed and sized in a quarry, the main aim has generally been to produce coarse graded aggregates of different sizes and road construction materials meeting certain specifications as per standards. As a part of normal production processes in quarries, a certain portion of the rock is reduced to such a size that it cannot be used as a part of coarse aggregates.

The production of coarse graded aggregates involves quarrying rock by drilling and blasting followed by a series of crushing and screening operations, until the desired grade is obtained. Aggregate quarry processes such as blasting, crushing and screening of coarse grade aggregates lead to the production of stone dust or quarry dust. Particle size of this quarry by-product is generally less than 5mm or depends upon the size of the lowest screening used. It consists of coarse, medium and fine sand particles as well as an appreciable amount of clay/silt fraction, i.e., finer than 75 micron size.

The production of crushed stone coarse aggregate starts with blasting of parent rock and fragmentation. The fragmented rock is then crushed and screened through multiple stages. Crushing of quarried rock is generally carried out in multiple stages: primary crushing, secondary crushing and tertiary crushing. By-product in the form of quarry dust is produced at the end of each stage and subsequently separated from coarse aggregate portion via screening.

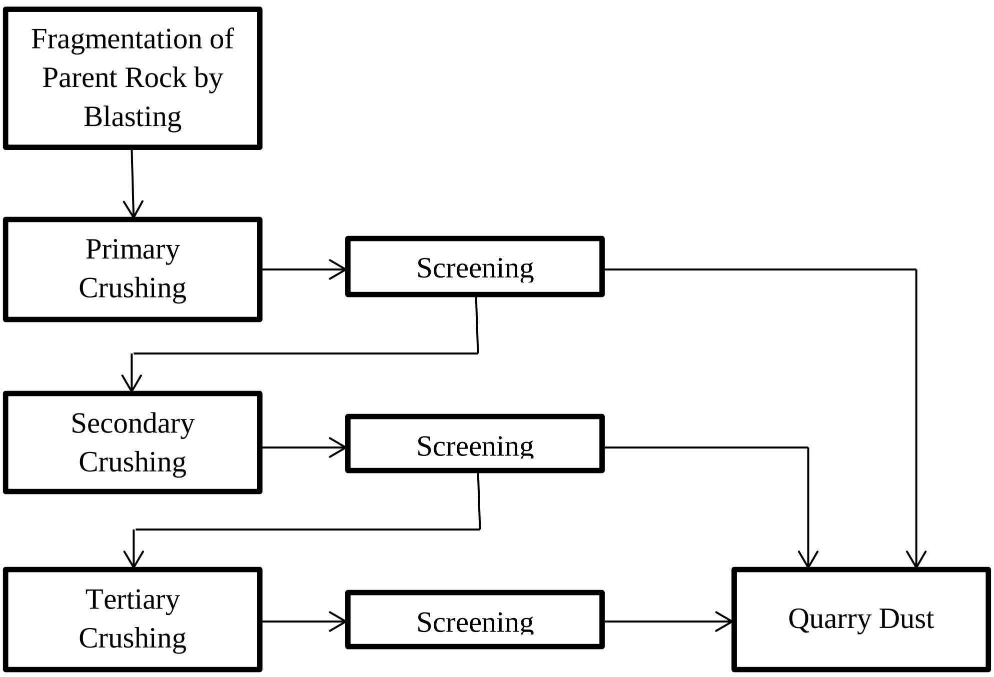

Fig. 1.1 : Schematic Diagram Showing the Production of Quarry Dust

Fig. 1.1 gives the schematic representation of different processes involved at a quarry, which lead to the production of quarry dust. It should be noted that different crusher types are used at primary, secondary and tertiary crushing stages. As a result, the by-products produced at the end of each stage may show different properties. Depending upon the type of quarry rock, quarry by-products can be up to 25% of the total aggregate produced. This reflects a high production rate of quarry dust at crushing plants.

1.4 Applications of Quarry Dust:

Quarry dust has a lot of applications in construction and infrastructure sector:

1. Quarry dust is used as a fine aggregate in bituminous mixes, i.e., Dense Bituminous Macadam (DBM), Bituminous Macadam (BM), Bituminous Concrete (BC), etc.
2. Quarry Dust is also used as a base and sub-base layers of Granular Sub Base (GSB), Wet Mix Macadam (WMM), etc. in highway construction.
3. It is used also in the manufacturing of some building materials such as bricks, tiles, lightweight aggregates etc.
4. Few more uses of quarry dust include embankment construction, landfill capping, etc.

However, its use in concrete is not very popular. The main objection in the way of using quarry dust as fine aggregate is that its grains are badly graded and contain a large amount of micro-fines. However, it can be used as a partial replacement of river sand in concrete so as to decrease the consumption of river sand. Proper design mix incorporating quarry dust as fine aggregate in concrete along with natural sand has a great potential to give concrete with identical or better properties as compared to conventional concrete.

1.5 Properties of Quarry Dust:

Quarry dust is different from natural sand in many aspects:

(i) Mineralogy – Natural sand is generally siliceous in nature, whereas the mineralogy of quarry dust depends upon the parent rock, from which it is made;

(ii) Micro-fine Content – The amount of micro-fines (material passing 75 micron sieve) is much higher in quarry dust as compared to natural sand;

(iii) Water absorption – Due to the higher amount of micro-fines, quarry dust has higher water absorption as compared to natural sand;

(iv) Particle Size Distribution – Natural river sand is generally uniformly graded, while quarry dust is normally badly graded or gap graded;

(v) Particle Shape – Natural sand particles are generally round in shape, while quarry dust particles are angular in nature;

(vi) Surface Texture – Natural sand particles have smooth surface texture, while quarry dust particles have rough surface texture.

As quarry dust is produced by crushing a large mass of rock, so many properties of the aggregate, i.e. chemical and mineralogical composition, petrographic classification, specific gravity, hardness, strength, physical and chemical stability, pore structure, colour etc., depend upon the properties of the parent rock. Some properties i.e. shape and size of particles, surface texture, water absorption etc., change due to crushing. The shape and size depends upon the nature and the degree of stratification of parent rock deposit, the type of crushing plant used and size-reduction ratio.

As quarry plants vary significantly in their degree of sophistication, in the range and extent of plant process controls and in the degree to which quarry raw feed is controlled to the plant, so the physical properties i.e. gradation, shape and size, surface texture, micro-fine content, surface morphology, etc., of quarry dust will be different for different crushing plants, even if the parent rock is same.

Typical physical properties of quarry dust used by different researches are summarised in Table 1.1. It can be observed that specific gravity of quarry dust varies from 2.59–2.83. Silt content may be as high as 15% and water absorption may be as high as 4.36%. Fineness modulus varies from 2.573–3.56.

Similarly, chemical composition of quarry dust used by different researchers are summarised in Table 1.2.

To have more idea about the mineralogical composition of quarry dust, X-Ray Diffraction (XRD) pattern of granite industry waste used as replacement of fine aggregate by Vijayalakshmi et. al. (2013) is given in Fig. 1.2.

TABLE 1.1 : Physical Properties of Quarry Dust Used in Different Researches

Property	Research Reported by				
	Shi-Cong and Chi-sun (2009)	**Raman et. al. (2011)**	**Naganathan et. al. (2012)**	**Omar et. al. (2012)**	**Singh et. al. (2016)**
Particle Size	Finer than 5mm	Finer than 5mm	Finer than 5mm	–	Finer than 4.75mm
Specific Gravity	2.61	2.83	2.59	2.61	2.622
Bulk Density	–	–	1720 kg/m^3	1680 kg/m^3	–
Water Absorption	–	0.78%	–	2.10%	4.36%
Silt Content	–	13%	7%	15.17%	–
Fineness Modulus	3.56	3.41	3.3	–	2.573

TABLE 1.2 : Chemical Composition of Quarry Dust Used in Different Researches

Chemical Composition (%)	Research Reported by				
	Omar et. al. (2012)	**Naganathan et. al (2012)**	**Dehwah (2012)**	**Ghannam et. al. (2016)**	**Jeyaprabha et. al. (2016)**
SiO_2	6.49	69.94	64.5	64.5	69.17
Al_2O_3	0.78	14.6	12.01	12.01	15.84
Fe_2O_3	0.36	2.16	5.77	5.77	1.16
CaO	34.95	2.23	4.8	4.8	8.04
MgO	14.44	0.38	0.57	0.57	–
SO_3	0.67	–	–	–	–
Na_2O	0.1	2.4	5.92	5.92	1.39
K_2O	0.4	6.91	5.26	5.26	0.43
TiO_2					
LoI	41	–	–	–	3.01

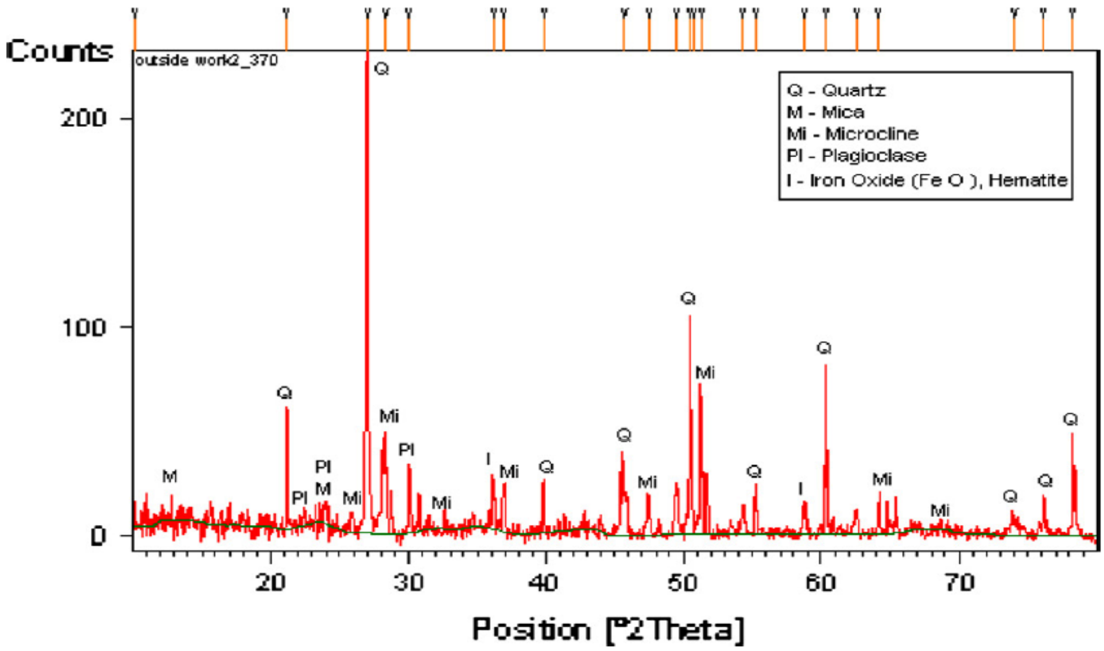

Fig. 1.2 : X-Ray Diffraction Pattern of Granite Industry By-Product [Vijayalakshmi et. al. (2013)]

To have an idea about morphology, particle shape and surface texture, etc., of quarry dust, Scanning Electron Microscope (SEM) image of granite dust given in a review article of Singh et. al. (2016) is given in Fig. 1.3.

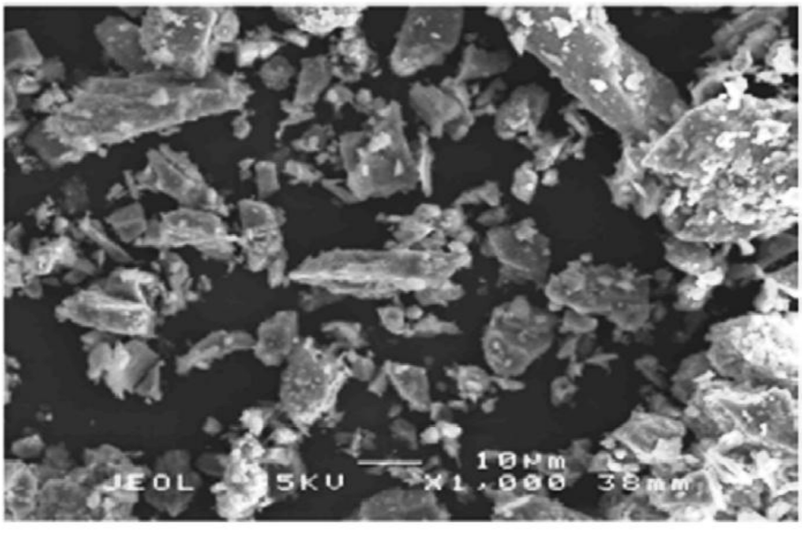

Figure 1.3 : SEM image of Granite Dust [Singh et. al.(2016)]

1.6 Specifications for Crushed Sand:

Although there are no standard specifications for quarry dust or stone dust, but just to have an idea, we can compare its properties with the standard specifications for crushed sand given in different standards. As crushed sand is different from river sand in many aspects, that's why, different standards have made some modifications in the requirements for crushed sands for use in concrete as fine aggregate.

British Standard, BS 882:1992 specifies the grading requirements of crushed sand, which are slightly different from that of natural sand. The difference is related to micro-fine content. BS 882:1992 allows a micro-fine content up to 16% by mass of crushed sand in normal concreting, while 9% by mass for heavy duty floors, whereas for natural sand the micro-fine content is only limited to 4% by mass. Moreover, the limit for material percent passing 150 micron sieve is also increased up to 20% for crushed sand, while for natural sand the same limit is only up to 15%. The comparison between the specifications of crushed sand and natural river sand given in BS 882:1992 is given in Table 1.3.

TABLE 1.3 : Comparison of Natural Sand and Crushed Sand Specifications as per BS 882-1992

Type of Fine Aggregate	% Passing 150 micron Sieve	% Passing 75 micron Sieve (Max)
Natural Sand	0-15	4
Crushed Sand	0-20	16 (9 for Heavy Duty Floors)

Similarly, in BIS 383:1970, the micro-fine content in crushed sand is increased up to 15%, which was 3% for natural sand. The limit for material % passing 150 micron sieve is also increased up to 20% for crushed sand, while for natural sand the same limit is only up to 10% for Zone I, II and III sand and 15% for Zone IV sand. The comparison between the specifications of crushed rock fine aggregate and natural river sand given in BIS 383:1970 is given in Table 1.4.

TABLE 1.4 : Comparison of Natural Sand and Crushed Sand Specifications as per BIS 383:1970

Type of Fine Aggregate	% Passing 150 micron Sieve	% Passing 75 micron Sieve (Max)
Natural Sand	0-10 (Zone I,II & III) 0-15 (Zone-IV)	3
Crushed Sand	0-20	15

Likewise, there are different grading requirements for crushed sands in different countries. For instance, Chinese National Standard, GB/T 14684-2001, specifies that the limit of the rock fines content in manufactured sand is, respectively, 3%, 5% and 7%, based upon the used concrete strength grade (defined as the 28 days compressive strength standard values) such as higher than 60MPa, between 60MPa and 30MPa and lower than 30MPa, respectively.

1.7 Objectives of the Thesis:

The main objective of the thesis is to study the potential of sandstone quarry dust to be used as a partial substitute of natural sand in concrete. In this study, concrete mixes are prepared with partial replacement of natural sand with sandstone quarry dust at different substitution rates of 10%, 20%, 30%, 40% and 50%, and different properties of concrete are compared with the control concrete mix containing 100% natural sand. Different objectives of this study are given below:

- To compare the workability of concrete mixes incorporating sandstone quarry dust as partial replacement of natural sand with control concrete mix.
- To compare the compressive strength, splitting tensile strength and density of concrete mixes incorporating sandstone quarry dust as partial replacement of natural sand with control concrete mix.
- To compare water absorption, sorptivity and chloride-ion permeability of concrete mixes incorporating sandstone quarry dust as partial replacement of natural sand with control concrete mix.

- To study various changes occurred in cement phases with inclusion of sandstone quarry dust as partial substitute of sand in concrete mixes by X-ray diffraction (XRD) analysis.
- To study the various changes occurred in microstructure of concrete with inclusion of sandstone quarry dust as partial substitute of sand in concrete mixes by Scanning Electron Microscope (SEM) analsysis.
- To find out the optimum percent replacement of natural sand with sandstone quarry dust so as to give acceptable workability, hardened and durability properties.

1.8 Outline of the Thesis:

This thesis report includes five chapters:

Chapter 1 "Introduction" gives some quantitative data about excessive sand mining in the world and its environmental impacts, use of industrial by-products as fine aggregate in concrete, production process and properties of quarry dust.

Chapter 2 "Literature Review" gives an overview about the previously published literature on the effect of different quarry dusts as a partial replacement of river sand in concrete.

Chapter 3 "Experimental Program" gives the detail of scheme of experimentation, different raw materials used and procedures adopted for testing of raw materials, mix design, casting, curing and methodology of various tests on concrete.

Chapter 4 "Results and Discussion" gives results of properties of raw materials and mix proportioning of concrete mixes. It also includes results and analysis of workability of concrete, hardened properties of concrete, i.e., density, compressive strength and splitting tensile strength, durability properties, i.e., water absorption, sorptivity and rapid chloride-ion permeability, mineralogical and microstructural characteristics & microstructural analysis, i.e., XRD and SEM analysis, of concrete mixes, incorporating sandstone quarry dust as a partial replacement of natural sand and results are compared with control concrete.

Chapter 5 Gives major conclusions drawn from the study.

CHAPTER 2
LITERATURE REVIEW

2.1 General

The effects of quarry dust as a replacement of river sand on the different properties of concrete have been reported since 1994. The early studies have only focused on normal strength concretes as well as mortars and it has been found out that use of inclusion of quarry dust as a replacement of river sand does modify many concrete properties i.e. fresh properties, hardened properties as well as durability properties. Since then, several researches have reported the effects of use of quarry dust as a part of fine aggregate in normal strength concrete, high strength concrete and mortars.

The purpose of this study is to access the current state of knowledge concerning the utilization quarry dust as replacement of natural or river sand in mortar and concrete. An extensive review of the recently published studies and available research papers on the use of quarry dust as a partial and full replacement of river sand is conducted in this literature review. Studies are examined in terms of measured fresh properties, hardened properties and durability properties. The key pointes arising from the literature review are discussed property-wise. Different properties studied in literature review are workability, compressive strength, splitting tensile strength, flexural strength, Young's modulus of elasticity, chloride-ion penetration, water permeability, water absorption, drying shrinkage and abrasion resistance.

2.2 Workability:

Shi-Cong and Chi-Sun (2009) investigated the effect of replacement of river sand with crushed fine stone at a replacement level of 25%, 50%, 75% and 100%. They observed that the control mix has the highest slump and as they increased the replacement of natural sand with crushed fine stone, workability of concrete decreased gradually. Slump of concrete with 100% river sand was found to be 60mm; while for concrete with 100% crushed fine stone, it was 30mm. They concluded that the decrease in workability with the incorporation of crushed fine stone in concrete is attributed to the angular shape of crushed fine stone, due to which these was an increase in water demand. Thus, more water was needed to produce a concrete with same workability as that of control concrete.

Raman et. al. (2011) investigated the effect of replacement of natural sand with quarry dust on workability of high strength rice hush ash concrete. Two series of concrete, C60 and C70, were made to achieve target strength of 60MPa and 70MPa, respectively. In each series, the replacement of natural sand with quarry dust was 10%, 20%, 30% and 40%, while for all mixes, 10% cement was replaced with rice hush ash. Due to the incorporation of superplasticizer, all concrete mixes of both the series exhibited very good workability and achieved the target minimum slump of 150mm. They observed that there was a decline in the workability of concrete mixes with the incorporation of quarry dust as partial replacement for sand in both of the series, C60 and C70. They concluded that the decline in workability is due to the presence of higher silt and fines content in quarry dust, which increase the specific surface area and consequently increases the water demand.

Vijayalakshmi et. al. (2013) investigated the effect of replacement of river sand with granite powder on workability of concrete at a replacement level from 0% to 25%. They observed that there is a decrease in workability of concrete with increase in substitution rate. Very poor workability was observed in the concrete mixtures with 20% and 25% substitution rate. They concluded that this decrease in workability is due to the difference of particle size distribution, particle shape and surface texture between river sand and granite powder. Granite powder was very fine as compared to natural sand with 90% particles finer than 50 micron, which increased the specific surface area of fine aggregate, consequently increasing the water demand. Due to the angular geometry and rough surface texture of granite powder particles, friction between the aggregate particles and paste increases. As a result, workability of concrete was reduced with increase in substitution of granite powder.

Singh et. al. (2016) investigated the effect of replacement of natural sand with granite cutting waste on workability of concrete at a replacement level form 0% to 40%. They observed that there is a significant decline in the workability of concrete with the increase in replacement of natural sand with granite cutting waste. They concluded that this decline in workability of concrete is due to the enhanced friction between the concrete particles as a result of the fact that granite cutting waste has relatively more angular and rough surface texture as compared to river sand.

Cordeiro et. al. (2016) investigated the effect of replacement of natural sand with crushed granite aggregate at replacement level of 10%, 30% and 50% on workability of concrete. They made a concrete with target strength of 50 MPa having slump in range of

200mm to 220mm. They observed that the dosage of superplasticizer was increased with increase in replacement level of natural sand with crushed granite aggregate. Superplasticizer dosage for control concrete was 0.16%, whereas for concrete with replacement level of 10%, 30% and 50% was increased to 0.17%, 0.19% and 0.23%, respectively. They concluded that the increase in dosage of superplasticizer indicated that with increase in crushed granite aggregate content, the water demand of concrete was increased.

The observations of all researches regarding the workability of concrete are summarized in Table 2.1.

TABLE 2.1: Summary of Workability Results of Different Researches

Research Reported by	**Test Method used**	**Replacement of Natural Sand with Quarry Dust (%)**										
		0	**5**	**10**	**15**	**20**	**25**	**30**	**40**	**50**	**75**	**100**
Shi-Cong and Chi-Sun (2009)	Slump (mm)	60	–	–	–	–	55	–	–	45	–	30
Raman et. al. (2011)	C60 Series Slump (mm)	200	–	175	–	170	–	165	155	–	–	–
	C70 Series Slump (mm)	220	–	200	–	190	–	190	180	–	–	–
Singh et. al. (2016)	Compaction Factor	0.93	–	0.91	0.88	0.86	0.84	0.81	0.80	–	–	–
Vijaya lakshmi et. al. (2013)	Slump (mm)	120	100	60	20	No Slump	No Slump	–	–	–	–	–

Bonavetti and Irassar (1994) investigated the fresh properties of mortar made by replacement of natural sand with three types of stone dusts, quartz dust, granite dust and limestone dust, respectively, at a replacement level of 0% to 20% for each stone dust. They observed that with increase in stone dust content, water content required to maintain constant flow is increasing. For 5% stone dust mortars, the increase in water demand is very small.

The increase was rapid when more than 10% stone dust was added. They concluded that this increase in water demand is because the stone dusts have larger surface area as compared to natural sand.

2.3 Compressive Strength:

Bonavetti and Irassar (1994) investigated compressive strength of mortar made by replacement of natural sand with three types of stone dusts, quartz dust, granite dust and limestone dust, respectively, at a replacement level of 0% to 20% for each stone dust at ages of 7, 28, 90 and 180 days of curing.. They observed that compressive strength of all mortars containing quartz dust was greater than control mortar at all test ages. the strength gain was in the order of 13 to 33% at 7 days, 6 to 21% at 28 days and 4 to 10% at later ages. For mortars containing granite dust, the strength of mortar at 5% replacement level was greater than control at age of 7 days. For mortars at 10%, 15% and 20% replacement level, the strength loss was 10 to 20%. After 28 days, there is an improvement in the compressive strength at 5% and 10% replacement, but at 15% and 20% replacement, compressive strength of mortar decreases. For mortars containing limestone dust, the compressive strength showed a strong increase of 44 to 72% at 7 days. After that, these mortars show compressive strength comparable to those of the control. This difference in behaviour is due to the difference in physical properties of stone dusts.

Jeyaprabha et. al. (2016) investigated the effect of incorporation of granite dust as a replacement of natural sand on compressive strength of mortar. They investigated the effect of 15% replacement of natural sand with granite dust at an age of 3, 7, 14 and 28 days of curing. They observed that there is an appreciable increase in compressive strength of mortar with incorporation of granite dust as replacement of natural sand at all ages. the enhancement of compressive strength of granite dust mortar as compared to river sand mortar for curing period of 3, 7, 14 and 28 days is 48%, 57%, 61% and 43%, respectively. They concluded that the enhancement of compressive strength of mortar with addition of granite dust as replacement of natural sand may be due to the filling effect of granite dust due to its high fineness as compared to natural sand.

Shi-Cong and Chi-Sun (2009) investigated the effect of replacement of river sand with crushed fine stone on compressive strength of concrete at a replacement level of 25%, 50%, 75% and 100% at 3, 7, 28 and 90 days of curing. They observed that the compressive strength of concrete was increased with the incorporation of crushed fine stone as replacement of river sand in concrete. It was noted that compressive strength was maximum at replacement level of 50% at all ages. However, there is a significant decrease in compressive strength of concrete at replacement levels of 75% and 100% as compared to control mix. This decrease in compressive strength was mainly attributed to the decrease in workability of concrete with the incorporation of crushed fine stone due to its angular shape. Thus 50% replacement can be regarded as optimum replacement level to give maximum compressive strength.

Raman et. al. (2011) investigated the effect of replacement of natural sand with quarry dust on compressive strength of high strength rice hush ash concrete. Two series of concrete, C60 and C70, were made to achieve target strength of 60MPa and 70MPa, respectively. In each series, the replacement of natural sand with quarry dust was 10%, 20%, 30% and 40%, while for all mixes, 10% cement was replaced with rice hush ash. Compressive strength of concrete was investigated at 1, 3, 7, 28, 56 and 365 days. It was observed that concrete made with 10% rice husk ash as replacement of cement and 20% quarry dust as replacement of sand has higher compressive strength in both of the series, especially after 28 days. This was due to the pozzolanic effect of rice husk ask, which did not come into effect at early ages. However, there is decrease in compressive strength of concrete at quarry dust replacement levels of 30% and 40% in both of the series. They concluded that it was due to the high amount of fines in quarry dust sample used, which not only interfere the bonding between aggregates and cement paste, but also decrease the workability of concrete by increasing water demand.

Omar et. al. (2012) investigated the effect of replacement of natural sand with limestone waste on compressive strength of concrete at a replacement level of 25%, 50%, and 75% at age of 7, 28 and 90 days. There was a significant improvement in compressive strength of concrete with increase in replacement level. At cement content of 350 kg/m^3, there is an increase of 13% and 12% in compressive strength of concrete, as compared to control mix, at 28 days at replacement level of 25% and 50%, respectively. Similarly, at cement content of 450 kg/m^3, there is an increase of 5% and 0.5% in compressive strength of concrete at 7 days and 28 days, respectively, at replacement level of 25%, as compared to control concrete. It was noted that at replacement levels of 50% and 75%, there is a reduction in compressive strength of concrete. They concluded that this reduction is attributed to the generation of large amount of calcium hydroxide from the hydration process of cement and limestone waste. Moreover, at higher replacement levels of 50% and 75%, there was an increase in fine powder content in concrete, which also contributed to the decrease in compressive strength.

Vijayalakshmi et. al. (2013) investigated the effect of replacement of river sand with granite powder on compressive strength of concrete at a replacement level from 0% to 25% at 7, 28 and 90 days of curing. It was observed that at early ages, inclusion of granite powder as replacement of sand showed better gain in strength as compared to control mix up to replacement level of 15%. They concluded that this was due to the denser matrix of granite powder waste and better dispersion of cement particles. Moreover, due to the siliceous property of granite powder, it act as nucleation sites for early hydration products and accelerate the hydration of cement. As a result there is a significant increase in C_3S content at early ages, which leads to the increase in compressive strength. The decrease in compressive strength at 20% and 25% replacement level was mainly attributed to very poor workability of concrete due to increase in water demand, which lead to improper compaction of concrete. At 28 days, concrete mixes up to 15% replacement level showed compressive strength comparable to control mix. It can be concluded that granite powder substitution rate up to 15% gave concrete with acceptable mechanical properties.

Rai et. al. (2014) investigated the compressive strength of mortar replacing natural sand with quarry dust at substitution rate of 20%, 50% and 100% at curing age of 3, 7, 28 and 50 days. They concluded that the compressive strength of mortar increases with increase in quarry dust content from 0% to 100% at early ages of 3 and 7 days. However, rate of increase in compressive strength decreases significantly, when natural sand was replaced by 50% and 100% with quarry dust at age of 28 days and 50 days. This decrease is very significant, when natural sand is completely replaced with quarry dust, which is about 13% and 4% at 28 and 50 days, respectively. At replacement level of 20%, there is an increase of 6% in compressive strength of mortar at ages of 28 and 50 days as compared to control mortar, whereas this increase is about 4% for the replacement level of 50%. So it can be concluded that 20% replacement of natural sand with quarry dust show the optimum reaction with optimum filling capacity. Thus, 20% replacement of natural sand with quarry dust will yield maximum compressive strength in cement mortar.

Singh et. al. (2016) investigated the effect of replacement of natural sand with granite cutting waste on compressive strength of concrete at a replacement level form 0% to 40% at age of 7 and 28 days. They observed that both 7 days and 28 days compressive strength exhibited similar trends. Initially, there was an increase in compressive strength with the increase in granite cutting waste replacement, but ultimately, exhibited a declining trend.

Optimum replacement level for maximum compressive strength was 25% at 7 days and 20% at 28 days. The enhanced compressive strength was mainly attributed to the filling effect of granite cutting waste and its rough surface texture, which improves bond between paste and particles. Once the replacement had achieved optimum level, further addition had negative impact on compressive strength of concrete due to the fact that now instead of acting as a filler material, it start increasing the specific surface area, thus required higher cement content. Since, cement content was constant in all mixes; this fact might be responsible for the decline in compressive strength.

Ghannam et. al. (2016) investigated the effect of replacement of river sand with granite powder on compressive strength of concrete at replacement from 0% to 20% at 7 days and 28 days of curing. They observed that there was a significant improvement in compressive strength with inclusion of granite powder as replacement of sand and compressive strength was maximum at replacement of 10%. There was an improvement of about 31%, 37%, 20% and 8% at replacement levels of 5%, 10% , 15% and 20%, respectively, as compared to control concrete, at 28 days. Similar enhancement in compressive strength was also observed at 7 days. Thus 10% replacement of natural sand with granite powder came out to be optimum to achieve maximum compressive strength.

Cordeiro et. al. (2016) investigated the effect of replacement of natural sand with crushed granite aggregate at replacement level of 10%, 30% and 50% on compressive strength of concrete at curing age of 7 and 28 days. They observed that with the inclusion of crushed granite aggregate, there was no negative impact on compressive strength of concrete at replacement levels of 10% and 30% at 7 days and 28 days. However, the compressive strength at 50% replacement was much higher as compared to control concrete, reaching 48.3 and 58.0 MPa after curing of 7 and 28 days, respectively.

2.4 Flexural Strength:

Bonavetti and Irassar (1994) investigated flexural strength of mortar made by replacement of natural sand with three types of stone dusts, quartz dust, granite dust and limestone dust, respectively, at a replacement level of 0% to 20% for each stone dust at ages of 7, 28, 90 and 180 days of curing. They observed that there is an improvement in flexural strength of mortar with incorporation of stone dust at all test ages. Only granite dust mortars at replacement levels of 5% and 20% showed a slight strength loss of about 2-5% after 90 days. It should be noted that the flexural strength of mortar showed a similar trend as that of compressive strength i.e. the increase in flexural strength is much more at early ages as compared to later ages.

Jeyaprabha et. al. (2016) investigated the effect of incorporation of granite dust as a replacement of natural sand on flexural strength of mortar. They investigated the effect of 15% replacement of natural sand with granite dust at an age of 28 days of curing on flexural strength of mortar. They observed that the inclusion of granite dust enhanced the flexural strength of mortar as compared to control concrete. This result was in accordance with other mechanical properties, as granite dust concrete also had better compressive strength as well as splitting tensile strength as compared to control mix.

Vijayalakshmi et. al. (2013) investigated the effect of replacement of river sand with granite powder on flexural strength of concrete at a replacement level from 0% to 25% at 28 days of curing. They observed that inclusion of granite powder as a replacement of river sand did not much affect the flexural strength of concrete at lower replacement levels of 5%, 10% and 15%. At these replacement levels, the flexural strength was similar or slightly lower than that of control concrete. However, increase in substitution rate beyond 15%, there was a significant decrease in flexural strength of concrete. This decrease in flexural strength can be attributed to poor workability of the concrete mixes at substitution rates of 20% and 25% due to increase in water demand of concrete, which lead to the improper compaction and poor interlocking between the cement paste and aggregate.

Singh et. al. (2016) investigated the effect of replacement of natural sand with granite cutting waste on flexural strength of concrete at a replacement level form 0% to 40% at age of 7 and 28 days. They observed that both 7 days and 28 days compressive strength exhibited similar trends. Initially, there was an increase in flexural strength with the increase in granite cutting waste replacement, but ultimately, exhibited a declining trend. Optimum replacement level for maximum flexural strength was 20% at 7 days as well as 28 days. It can be observed that at 28 days, all concrete mixes with granite cutting waste had flexural strength values close to 6MPa and the decline in flexural strength even at the replacement level of 40% is very small. The enhanced flexural strength was mainly attributed to the filling effect of granite cutting waste and its rough surface texture, which improves bond between paste and particles. Once the replacement had achieved optimum level, further addition had negative impact on flexural strength of concrete due to the fact that now instead of acting as a filler material, it start increasing the specific surface area, thus required higher cement content. Since, cement content was constant in all mixes; this fact might be responsible for the decline in flexural strength.

Ghannam et. al. (2016) investigated the effect of replacement of river sand with granite powder on flexural strength of concrete at replacement from 0% to 20% at 7 days and 28 days of curing. They observed that concrete mixes with granite dust had higher flexural strength as compared to control mix. There was an improvement of about 12%, 43%, 8% and 0.3% at replacement levels of 5%, 10% , 15% and 20%, respectively, as compared to control concrete, at 28 days. Similar enhancement in compressive strength was also observed at 7 days. It can be concluded that the optimum replacement level of granite dust to achieve maximum flexural strength was 10%. It should be noted that this optimum content is same as that of compressive strength, which was also 10%, but different from that of splitting tensile strength, which was 15%.

2.5 Splitting Tensile Strength:

Jeyaprabha et. al. (2016) investigated the effect of incorporation of granite dust as a replacement of natural sand on splitting tensile strength of mortar. They investigated the effect of 15% replacement of natural sand with granite dust at an age of 28 days of curing. They observed that specimen with 15% granite dust show an increase in splitting tensile strength of concrete as compared to river sand mortar. This trend was in accordance with the compressive strength test result, which also showed an increase at 28 days.

Vijayalakshmi et. al. (2013) investigated the effect of replacement of river sand with granite powder on splitting tensile strength of concrete at a replacement level from 0% to 25% at 28 days of curing. They observed that inclusion of granite powder as a replacement of river sand did not much affect the splitting tensile strength at lower replacement levels of 5%, 10% and 15%. At these replacement levels, the splitting tensile strength was similar or slightly lower than that of control concrete. However, increase in substitution rate beyond 15%, there was a significant decrease in splitting tensile strength of concrete. This decrease in splitting tensile strength can be attributed to poor workability of the concrete mixes at substitution rates of 20% and 25% due to increase in water demand of concrete, which lead to the improper compaction and poor interlocking between the cement paste and aggregate.

Ghannam et. al. (2016) investigated the effect of replacement of river sand with granite powder on splitting tensile strength of concrete at replacement from 0% to 20% at 7 days and 28 days of curing. They observed that there was a significant improvement in splitting tensile with inclusion of granite powder as replacement of sand. There was an improvement of about 4%, 15% and 29% at replacement levels of 5%, 10% and 15%, respectively, as compared to control concrete, at 28 days. Similar enhancement in compressive strength was also observed at 7 days. However, there was a decrease in splitting tensile strength of concrete at replacement level of 20%. Thus the optimum content of granite dust to be used as a replacement of sand to get maximum splitting tensile strength comes out to be 15%. It should be noted that this optimum content is different from that of compressive strength, which was 10%. Moreover, the percent increase in splitting tensile strength was lower than that of compressive strength.

2.6 Modulus of Elasticity:

There is not much literature available on the effect of stone dust or quarry dust as a replacement of natural sand on modulus of elasticity of concrete.

Cordeiro et. al. (2016) investigated the effect of replacement of natural sand with crushed granite aggregate on modulus of elasticity of concrete for a replacement level of 10%, 30% and 50%. They observed that there was no significant change in modulus of elasticity of concrete with increase in replacement level. All concrete mixes had modulus of elasticity close to that of control concrete. Young’s modulus of elasticity for control mix was 23.9 GPa, whereas, it was 23.0, 23.7 and 24.2 for the concrete mixes containing 10%, 30% and 50% granite dust, respectively. This behaviour was attributed to good quality of granite dust used for natural sand replacement.

2.7 Chloride-ion Penetration:

Shi-Cong and Chi-Sun (2009) investigated the effect of replacement of river sand with crushed fine stone on compressive strength of concrete at a replacement level of 25%, 50%, 75% and 100% at age of 28 and 90 days of curing. They observed that there is an increase in chloride-ion penetration with increase in replacement of river sand with crushed fine stone. Total charge passed was minimum for control mix and maximum for concrete mix containing 100% crushed fine stone as fine aggregate. However, it can be observed that chloride-ion penetration of concrete mix containing 25% crushed fine stone is almost comparable to control concrete. For all concrete mixes, total charge passed was in the range of 5600-6000 coulombs, i.e., the increase in total charge passes was not much. The increase in chloride-ion penetration is mainly attributed to the poor compaction due to decrease in workability of concrete with the increase in crushed fine stone content in concrete, resulting poorer microstructure.

Vijayalakshmi et. al. (2013) investigated the effect of replacement of river sand with granite powder on chloride-ion permeability of concrete at a substitution rate from 0% to 25% at 180 and 365 days. They observed that the chloride-ion permeability of concrete is directly proportional to the substitution rate, i.e., with the increase in replacement of natural sand with granite powder, chloride-ion permeability of concrete mixes increased. The chloride-ion permeability of concrete mixes at lower substitution rates of 5%, 10% and 15% was almost equivalent to control mixes. Up to 15% substitution rate, charge passed was less than 1500 coulombs, whereas, up to substitution rate of 10%, charge passed was less than 1000 coulombs, which can be regarded as very low. Concrete mixes with 20% and 25% replacement level showed highest chloride-ion penetration, for which charge passed was more than 1500 coulombs. This increase in chloride-ion penetration was attributed to decrease in workability of concrete with increase in substitution rate of granite powder, which led to improper compaction and a porous microstructure.

Singh et. al. (2016) studied the behaviour of concrete made by replacing river sand with granite dust under adverse exposure conditions. Along with several other properties, they studied the effect of replacement of river sand with granite dust at replacement levels of 10%, 25%, 40%, 55% and 70% on chloride-ion penetration at age of 28 days, 56 days and 90 days, respectively, at two different w/c ratios of 0.3 and 0.4 each. They reported conflicting results with the previous studies. At both w/c ratios, chloride-ion penetration was decreased up to 25% replacement of river sand with granite dust and it showed an increasing trend onwards. At all ages of testing, concrete mix with 25% replacement of natural sand with granite dust had minimum chloride-ion penetration depth, at both w/c ratios. They concluded that the decrease in depth of chloride-ion penetration was due to improved microstructure of concrete due to micro filler addition and also better bonding between granite particles and cement paste due to rough and angular surface texture. Being finer than river sand, granite dust initially acted as filler and enhanced the density of the cement matrix. However, at higher replacement levels, granite dust adversely affects the gradation of fine aggregate, which leads to a poorer microstructure of concrete. As a result, there is an increase in chloride-ion penetration depth after 25% replacement onwards.

2.8 Water Permeability:

Omar et. al. (2012) investigated the effect of replacement of natural sand with limestone waste on water permeability of concrete at a replacement level of 50% at age of 28 days at two different cement contents.. They observed that as the dust content in concrete was increased, coefficient of water permeability decreased. At cement content of 350 kg/m^3, coefficient of water permeability for control concrete was 6.8×10^{-10} cm/sec, while for the mix containing 50% limestone waste, it was reduced to 4.87×10^{-10} cm/sec. Similarly, at cement content of 450 kg/m^3, coefficient of water permeability for control concrete was 6.03×10^{-10} cm/sec, while for the mix containing 50% limestone waste, it was reduced to 5.13×10^{-10} cm/sec. The decrease in water permeability was attributed to filling effect of limestone waste micro-fines, which tend to fill up the voids and improved the impermeability of concrete, blocking the passages connecting capillary pores and water channels.

Vijayalakshmi et. al. (2013) investigated the effect of replacement of river sand with granite powder on water permeability of concrete at a substitution rate from 0% to 25% at 180 and 365 days. They observed that the coefficient of water permeability was increased with increase in replacement of natural sand with granite powder. However, the water permeability of concrete mixes at lower substitution rates of 5%, 10% and 15% showed low permeability. Concrete mixes with substitution rates of 20% and 25% showed very sharp increase in coefficient of water permeability. Concrete containing 25% granite powder had coefficient of water permeability of 15.21×10^{-12} m/sec, which is more than the maximum recommended value of coefficient of water permeability of 15×10^{-12} m/sec as per ACI 301-89. This reason behind this behaviour was also attributed to decrease in workability of concrete with increase in substitution rate of granite powder, which led to improper compaction and a porous microstructure.

Singh et. al. (2016) investigated the effect of replacement of natural sand with granite cutting waste on water permeability of concrete at a replacement level form 0% to 40%. They recorded a significant decrease in water permeability of concrete with increase in replacement of natural sand with granite cutting waste. All concrete mixes containing granite cutting waste has lower water permeability as compared to control mix and concrete mix with replacement level of 30% had minimum water permeability. They concluded that the decrease in water permeability of concrete mixes was due to the fact that addition of granite dust as a replacement of natural sand made the concrete matrix denser and reduced the number of voids as well as capillaries within concrete matrix domain.

2.9 Water Absorption:

There is not much literature available on the effect of stone dust or quarry dust as a replacement of natural sand on water absorption of concrete.

Cordeiro et. al. (2016) investigated the effect of replacement of natural sand with crushed granite aggregate on water absorption of concrete for a replacement level of 10%, 30% and 50% at 28 days of curing. They observed that with increase in replacement of natural sand with granite dust, water absorption of concrete mixes was decreased. Water absorption of control concrete was found to be 5.1%, whereas, water absorption of concrete mixes with replacement levels of 10%, 30% and 50% was recorded as 5.0%, 4.0% and 3.4%, respectively. Thus, concrete mix incorporating maximum stone dust had the lowest water absorption. This behaviour can be attributed form the fact that due to the presence of micro-fines, granite dust tend to fill up the voids in concrete and made the concrete mix more dense, resulting a decrease in water absorption. Thus, it can be concluded that the inclusion of crushed granite aggregate had positive effect on water absorption of concrete. However, they insisted that further research is needed to confirm these findings.

2.10 Drying Shrinkage:

There is not much literature available on the effect of stone dust or quarry dust as a replacement of natural sand on drying shrinkage of concrete.

Shi-Cong and Chi-Sun (2009) investigated the effect of replacement of river sand with crushed fine stone on drying shrinkage of concrete at a replacement level of 25%, 50%, 75% and 100% at 112 days. They observed that drying shrinkage of all concrete mixes containing crushed fine stone was lower than that of control concrete. They concluded that drying shrinkage of concrete is significantly affected of specific surface area of aggregate. Concrete made with aggregates having lower specific surface area have lower drying shrinkage. The decrease in drying shrinkage was due to the fact that crushed fine stone used for making concrete had lower specific surface area as compared to river sand due to its larger particle size distribution. Thus, it can be concluded that the inclusion of crushed fine stone as replacement of river sand had positive effect on drying shrinkage of concrete.

2.11 Abrasion Resistance:

There is not much literature available on the effect of stone dust or quarry dust as a replacement of natural sand on abrasion resistance of concrete.

Singh et. al. (2016) investigated the effect of replacement of natural sand with granite cutting waste on abrasion resistance of concrete at a replacement level form 0% to 40%. They observed that depth of wear for concrete containing granite cutting waste as replacement of natural sand was lower than that of control mix. Depth of wear of concrete containing granite cutting waste, except concrete with 40% replacement level, was less than that of control concrete. The minimum depth of concrete was recorded for concrete containing 20% granite cutting waste. Thus, it can be concluded that the inclusion of granite cutting waste had positive effect on abrasion resistance of concrete.

2.12 Carbonation Depth:

There is not much literature available on the effect of stone dust or quarry dust as a replacement of natural sand on carbonation of concrete.

Vijayalakshmi et. al. (2013) investigated the effect of replacement of river sand with granite powder on carbonation depth of concrete at a substitution rate from 0% to 25% at 180 and 365 days. They concluded that there was an increase in carbonation depth of concrete with increase in substitution rate of granite powder as replacement of river sand as well as with age. All carbonation depth values at 365 days were higher than the corresponding values at 180 days. Carbonation depth for concrete mixes with substitution rate of 5%, 10% and 15% was close to that to control concrete and concrete with substitution rate of 5% had carbonation depth almost equal to control concrete at both ages. However, there is a sharp increase in carbonation depth beyond the substitution rate of 15%. The carbonation depth at substitution rate of 20% and 25% was 8.9mm and 10.2mm at age of 365 days, which was closer to the cover of reinforcing bars and might cause corrosion, hence, not recommended in RCC. This increase in carbonation depth with increase in substitution rate can be attributed to the poor workability of concrete mixes, resulting poor compaction. Thus, replacement of 15% sand with granite powder was regarded as optimum and replacement beyond that was not advisable.

Singh et. al. (2016) studied the behaviour of concrete made by replacing river sand with granite dust under adverse exposure conditions. Along with several other properties, they studied the effect of replacement of river sand with granite dust at replacement levels of 10%, 25%, 40%, 55% and 70% on carbonation at different ages, at two different w/c ratios of 0.3 and 0.4 each. They reported conflicting results with the previous study. At all ages and at both w/c ratios, carbonation depth was minimum for the concrete with 25% replacement of natural sand with granite dust, and onwards, it showed an increasing trend. The trend was same as reported by them in case of chloride-ion penetration depth. They concluded that the decrease in carbonation depth was due to improved microstructure of concrete due to micro filler addition and also due to better bonding between granite particles and cement paste due to rough and angular surface texture. Being finer than river sand, granite dust initially acted as filler and enhanced the density of the cement matrix. However, at higher replacement levels, increase in specific surface area of fine aggregate required more cement content for proper bonding, which lead to porous microstructure of concrete.

CHAPTER 3
EXPERIMENTAL PROGRAM

3.1 General:

The chapter describes the details of experimental program and methodology for the evaluation of fresh properties (workability), hardened properties (density, compressive strength and splitting tensile strength), durability properties (chloride-ion permeability, sorptivity and water absorption) and mineralogical & microstructural characteristics (X-Ray diffraction, i.e., XRD and Scanning Electron Microscopic, i.e., SEM) of concrete mixes made with varying percentages of sandstone quarry dust as partial replacement of natural sand. In this chapter, procedures adopted for physical testing of constituent materials, i.e., cement, coarse aggregate, natural sand and sandstone quarry dust, used for making concrete are described. This chapter also includes procedure adopted for mix design of concrete, details of test specimens to carry out different tests, procedure of casting as well as the test procedures adopted, age of specimen at testing, are also discussed in this chapter. Flow chart showing a general overview of the experimental program is given in Fig. 3.1.

3.2 Testing of Constituent Materials:

3.2.1 Cement Testing:

Ordinary Portland Cement of Grade 43 (OPC 43), manufactured by UltraTech Cement Limited, was used in all concrete mixes. Physical properties of cement, i.e., fineness, soundness, standard consistency, initial and final setting time, compressive strength, specific gravity, are evaluated by the procedures given in Bureau of Indian Standard specifications. Fineness of cement was tested as per procedure given in BIS 4031(Part 1):1996, by sieving through 90 micron sieve. Soundness was tested as per the procedure of BIS 4031(Part 3):1988, by Le-Chatlier apparatus. Standard consistency and initial and final setting time are tested as per IS 4031(Part 4):1988 and BIS 4031(Part 5):1988, respectively, by Vicat apparatus. Compressive strength of cement is tested as per the procedure of BIS 4031(Part 6):1988. 1:3 cement mortar cubes were made having dimensions 70.6mm×70.6mm×70.6mm using standard sands conforming to BIS 650:1991. These cubical specimen were tested at compression testing machine (CTM) conforming to BIS 516:1959 at loading rate of

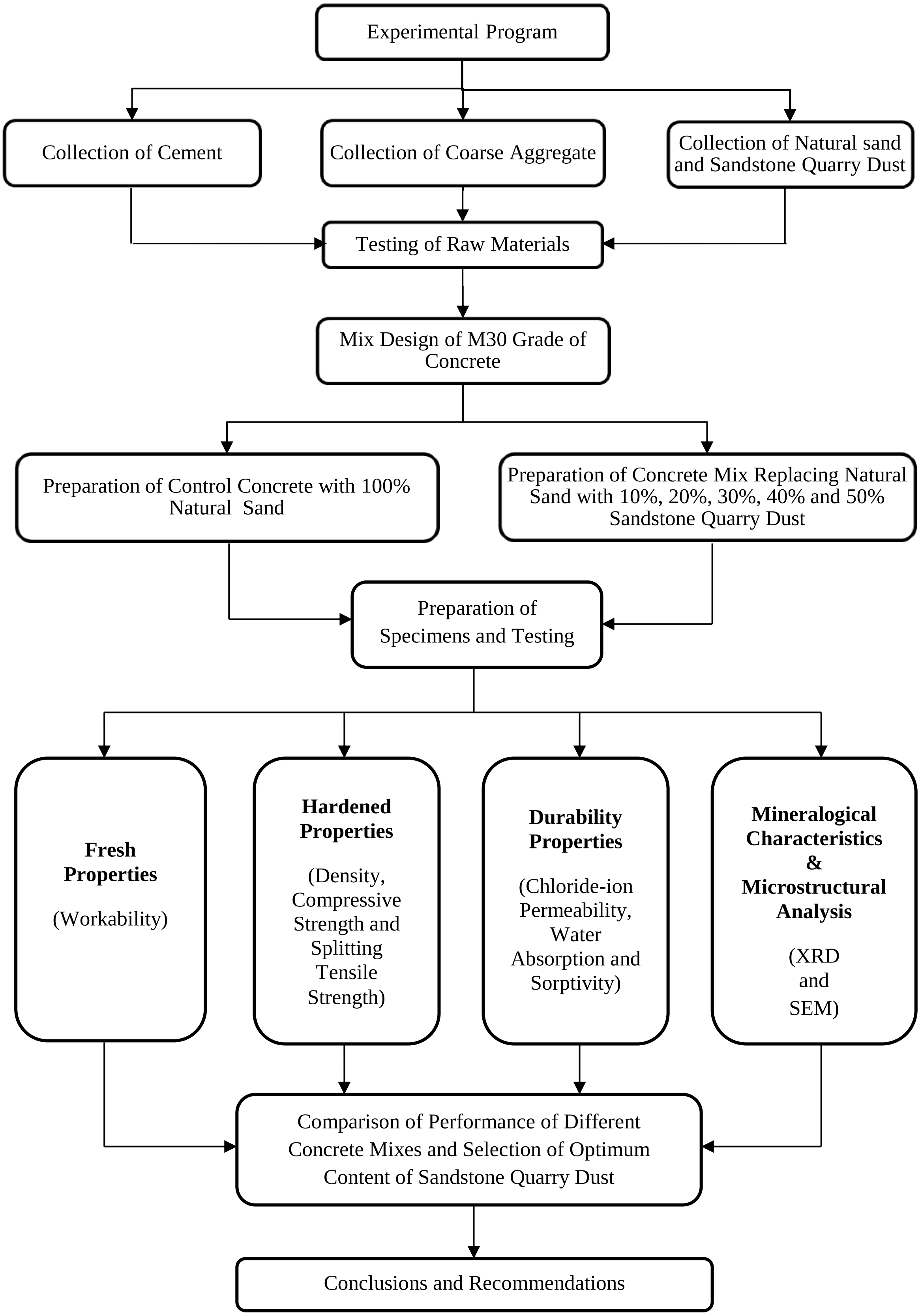

Fig. 3.1 : Flow Chart of Experimental Program

70kN/minute to evaluate compressive strength of cement-mortar cubes at age of 3, 7 and 28 days. Specific gravity of cement was tested as per the procedure of BIS 4031(Part 11):1988, using density bottle method. All the physical properties of cement must satisfy the requirements given in BIS 8112:1989.

3.2.2 Coarse Aggregate:

A combination of 20mm nominal size aggregate and 10mm nominal size aggregate is used as coarse aggregate in this experimental program. Both types of coarse aggregate were locally procured. Physical properties of both types of coarse aggregate, i.e., sieve analysis, specific gravity, water absorption and bulk density, are evaluated by the procedures given in Bureau of Indian Standard specifications. Aggregates were sieved through a set of sieves to obtain sieve analysis as per the procedure given in BIS 2386(Part 1):1988 and compared with the requirements given in BIS 383:1970. Specific gravity, water absorption and bulk density of coarse aggregate were tested as per the procedure given in BIS 2386(Part 3):1963. For calculation of specific gravity of both type of coarse aggregate, water basket method was used.

3.2.3 Natural Sand:

Locally procured natural sand was used as fine aggregate in concrete. Physical properties of natural sand, i.e., sieve analysis, specific gravity, water absorption and bulk density, are evaluated by the procedures given in Bureau of Indian Standard specifications. Natural sand was sieved through a set of sieves to obtain sieve analysis as per the procedure given in BIS 2386(Part 1):1988 and compared with the requirements given in BIS 383:1970. As per the requirements of BIS 383:1970, zone of the sand was determined and fineness modulus was calculated. Specific gravity, water absorption and bulk density of natural sand was tested as per the procedure given in BIS 2386(Part 3):1963. Specific gravity of natural sand was calculated by piconometer method.

3.2.4 Sandstone Quarry Dust:

Sandstone quarry dust was collected form a local crushing plant situated in district Mansa, Punjab. Sandstone quarry dust was sieved through a set of sieves to obtain sieve analysis as per the procedure given in BIS 2386(Part 1):1963, so as to compare its particle size distribution with natural sand. The sieve analysis results of sandstone quarry dust were also compared with the grading requirements for crushed sands given in BIS 383:1970. Like natural sand, zone and fineness modulus of sandstone quarry dust was determined. Specific gravity, water absorption and bulk density of quarry dust was tested as per the procedure given in BIS 2386(Part 3):1963. Piconometer method was used for specific gravity test. To have an idea about different minerals present in sandstone quarry dust, X-ray diffraction (XRD) technique was used. Scanning Electron Microscope (SEM) analysis was used to know about the particle shape and surface texture of the fine dust particles. Energy Dispersive Spectra (EDS) was used to know approximate chemical composition of sandstone quarry dust.

3.3 Mix Proportioning of Concrete Ingredients:

All-In aggregate grading for 20mm nominal size aggregate as the requirements given in BIS 383:1970 was used to fix the proportion of aggregate in concrete. Trial and error method was used to fix the proportion of 20mm nominal size aggregate, 10mm nominal size aggregate and natural sand in concrete based on their individual gradations. Based upon this all-in aggregate grading, percentage of 20mm nominal size aggregate, 10mm nominal size aggregate and natural sand was fixed, which was to be used in the calculation of quantities of coarse aggregate and fine aggregate at the time of mix design.

Mix design of concrete was done as per IS 10262:2009. Grade of control concrete was chosen as M30 and target slump was 100mm. Conditions for exposure were taken as moderate. As per the procedure of IS 10262:2009, first of all, target strength was calculated assuming suitable value of standard deviation. Estimated water content was calculated for the desired workability and free w/c ratio was chosen from experience as per the target strength of concrete to be achieved. From estimated water content and free w/c ratio, cement content was calculated. Based on the volume of aggregate in concrete, quantity of coarse as well as fine aggregate was calculated as per their specific gravity and proportion fixed as per all-in aggregate grading. Coarse aggregate and fine aggregate quantities calculated were based upon the SSD (Saturated Surface Dry) condition. Thus, necessary water corrections must be applied based upon the moisture content of coarse aggregate and fine aggregate at the time of casting.

Based upon the quantities of different ingredients in control concrete, mix proportions of concrete mixes with sandstone quarry dust were calculated. Concrete mixes with replacement of natural sand with 10%, 20%, 30%, 40% and 50% quarry dust were designated as QD10, QD20, QD30, QD40 and QD50, respectively.

3.4 Mixing of Ingredients and Casting of Samples:

3.4.1 Mixing of Ingredients:

Laboratory drum mixer was used for the preparation and mixing of all concrete mixtures. A drum mixer is a mechanical device, which uses a revolving drum to combine cement, coarse aggregate, fine aggregate and water to form a homogenous mass. Both, coarse aggregate as well as fine aggregate, were in dry conditions. So, necessary water corrections were applied before the mixing operation. All the ingredients, i.e., cement, coarse aggregate, fine aggregate and water, were weighted with an accuracy of 1.0 gram. Drum mixer was started and firstly, coarse aggregate and fine aggregate were dry mixed thoroughly. After that, cement was added in the drum mixer and it was rotated till a uniform mass was obtained. In the end, water was added very carefully, so as to prevent any loss of water during the mixing operations. The drum mixer was rotated till we got a concrete mass with uniform colour and consistency. Care was taken during the whole operation so as to ensure the proper mixing of all ingredients. Workability of all concrete mixtures was checked immediately after the finishing of mixing operation.

3.4.2 Sample Preparation:

All the concrete specimens were casted in steel moulds. All the moulds were cleaned and oiled properly before the mixing of concrete ingredients. They were properly tightened to correct dimensions before casting operations. Care was taken to ensure that there must not be any gap left so as to prevent the leakage of slurry. Concrete specimens were compacted in two layers using vibrating table. After the casting operations, concrete specimens were left in the casting room for approximately 24 hours, after which they were de-moulded and placed in the curing tank. The detail of the specimens casted to perform various tests is given below:

1. *Compressive Strength*: Cubical specimens of dimensions 150mm×150mm×150mm were casted for testing of compressive strength of concrete.

2. *Splitting Tensile Strength*: Cylindrical specimens of diameter 150mm and height 300mm were casted for testing of splitting tensile strength of concrete.
3. *Water Absorption*: Cubical specimens 70.6mm×70.6mm×70.6mm were casted for testing of water absorption of concrete.
4. *Sorptivity:* Cylindrical specimens of diameter 100mm and height 50mm were casted for testing of sorptivity of concrete
5. *Rapid Chloride-Ion Permeability*: Cylindrical specimens of diameter 100mm and height 50mm were casted for testing of rapid chloride-ion permeability of concrete.

3.4 Test Procedures:

3.4.1 Workability:

Workability of concrete is the ease with which concrete can be properly mixed, transported, compacted and finished, with minimum loss in homogeneity. Slump test is the most extensively used test to measure workability of concrete all around the world in construction sector. Workability of the concrete was evaluated by slump test as per Indian Standard Specifications given in BIS 1199:1959. A mould in the form of frustum of a cone with bottom diameter 200mm, top diameter 100mm and height 300mm was filled with four approximately equal layers, tempering each layer with a standard tempering rod with 25 strokes.

Figure 3.2 : Slump Test of Concrete

After filling and levelling the surface, mould was removed by lifting it in vertical direction, allowing concrete to subside. Results of the workability testing were reported as slump in mm, which is the difference between height of the mould and that of highest point of subsided concrete mass.

3.4.2 Compressive Strength:

Compressive strength is regarded as the most important property of hardened concrete. Compressive strength test was done as per Indian Standard Specifications, according to the procedure given in BIS 516:1959. Compressive strength of concrete was evaluated at age of 7 days, 28 days and 90 days using standard cube specimens of 150mm×150mm×150mm. Compression Testing Machine (CTM) of 5000 kN capacity was used for the testing of compressive strength of concrete. Concrete specimen were demoulded 24 hours after the casting and placed in the curing tank to ensure sufficient curing. At each specified age, specimen was placed centrally between the bearing plates of CTM and load was applied continuously and uniformly at specified loading rate of 140 kg/cm^2/min. the load was increased until the specimen broke and the maximum load taken by each specimen was noted down.

Figure 3.3 : Compressive Strength Test on Compression Testing Machine

The compressive strength was calculated according to the following formula:

$$\sigma = P/A$$

where,

σ = Compressive Strength (N/mm^2)

P = Maximum load sustained by the cube (N)

A = Area of cross section of cube (mm^2)

Results of the compressive strength testing were reported as average of compressive strength of 3 specimens at 7 days, 28 days and 90 days for each concrete mix in N/mm^2.

3.4.3 Density of Concrete:

Density of concrete is an important aspect, as it plays a major role in the calculation of dead weight of a structure. At the time of demoulding of cubical specimens of 150mm×150mm×150mm used for testing of compressive strength, mass of 3 random cubes was taken using a weighing balance of 10 kg capacity with an accuracy of 1.0g and 1-day density of concrete was calculated from the following formula:

$$\rho = M / V$$

where,

ρ = Density of concrete in kg/m^3

M = Mass of 150mm×150mm×150mm cube in kg

V = Volume of cube in m^3

3.4.4 Splitting tensile Strength:

As concrete is strong in compression, but very weak in tension, so it is necessary to determine the tensile strength of the concrete so as to prevent cracking in tension zones. Splitting tensile strength is an indirect method to determine tensile strength of concrete. Splitting tensile strength test was done as per Indian Standard Specifications, according to the procedure given in BIS 5816:1999. Splitting tensile strength of concrete was evaluated at age of 7 days, 28 days and 90 days using standard cylindrical specimens of 150mm diameter and 300mm height. Concrete specimen were demoulded 24 hours after the casting and placed in the curing tank to ensure sufficient curing. Compression Testing Machine (CTM) of 5000 kN capacity was used for the testing of compressive strength of concrete. For the evaluation of splitting tensile strength, each specimen was placed centrally between the bearing plates of CTM with suitable packing strips at top and bottom to ensure proper distribution of load as shown in Figure 3.4. Load was applied continuously and uniformly at specified loading rate of 1.2 $N/mm^2/min$ to 2.4 $N/mm^2/min$. The load was increased until the specimen cracked along the vertical plane and the maximum load taken by each specimen was noted down. The splitting tensile strength was calculated according to the following formula:

$$\sigma_{st} = 2P/\pi DL$$

where,

σ_{st} = Splitting Tensile Strength (N/mm^2)

P = Maximum load sustained by the cylinder (N)

D = Diameter of cylinder (mm)

L = Length of cylinder (mm)

Results of the splitting tensile strength testing were reported as average of splitting tensile of 3 specimens at 7 days, 28 days and 90 days for each concrete mix in N/mm^2.

Fig. 3.4 : Splitting Tensile Strength Test of Concrete

3.4.5 Water Absorption:

Pore structure of concrete plays a very important role to have an idea about the durability aspects of concrete. Water absorption of concrete is an indicator of how dense the microstructure of concrete is. Water absorption of concrete was evaluated at various specified ages as per the procedure given in ASTM C 642 − 13.

As per the standard procedure, there are no specifications given regarding the shape and size of the specimens for water absorption test, except that the volume of each individual specimen shall not be less than 350 cm^3, with weight of more than 800g and each portion shall be free from observable cracks, fissures and shattered edges. Water absorption test was performed at 7 days and 28 days, after initial curing of 28 days on cubical specimens of 70.6mm × 70.6mm × 70.6mm. Oven dry mass and saturated mass of the concrete specimens were determined as per the standard procedures given in ASTM C 642 − 13. Water absorption of concrete was calculated using the following formula:

$$\text{Absorption after Immersion (\%)} = [(B - A)/A] \times 100$$

where,

B = Oven Dried mass of specimen in air (g)

A = Mass of surface-dry specimen after immersion in air (g)

Results of water absorption testing were reported as average of water absorption of 3 specimens at 7 days and 28 days after initial curing of 28 days for each concrete mix in %.

3.4.6 Sorptivity:

Movement of liquids through interconnecting pores plays a very important role to determine the durability of concrete. Sorptivity of concrete is rate of absorption of water by one dimensional capillary action. Sorptivity of concrete was evaluated as per the procedure given in ASTM C 1585 − 04. Rate absorption of water test was performed at 7 days and 28 days, after initial curing of 28 days on standard cylindrical specimens of 100mm diameter and 50mm height. Each specimen was prepared as per the procedure give in ASTM C 1585 − 04. Sides of the specimen were sealed with epoxy coating and adhesive tape was wrapped over the outer curved surface. Mass of each specimen was taken and it was recorded as initial mass. The schematic diagram of the experimental procedure is given in Figure 3.5. As soon as the specimen was placed in water, a stop watch had been started and mass of the specimen was taken after 5, 10, 20, 30, 60, 120, 180, 240 and 360 minutes. At each specified time slot, specimen was lifted and its surface in contact with water was surface dried with the help of a towel and its mass was recorded.

For calculation of Sorptivity of concrete specimen, first of all, rate of absorption of water, I, was calculated using change in mass of the specimen divided by the product of the ross-sectional area of the test specimen and density of water. For this purpose, density of water shall be adopted as 0.001 g/mm^3 and the unit of I comes out to be mm^3/mm^2 or mm.

$$I = m_t / (a*d)$$

Where,

I = Rate of absorption (mm^3/mm^2 or mm)

M_t = the change in specimen mass at time t (g)

a = Exposed area of the specimen (mm^2)

d = Density of water (g/mm^3)

Now, rate of absorption of water, I, was plotted against square root of time in min, $t^{0.5}$ and curve was obtained. By linear regression analysis, slope of the curve was obtained. This slope of the curve is regarded as Sorptivity with units mm^3/mm^2/min$^{0.5}$ or mm/min$^{0.5}$. Results of sorptivity testing were reported as average of sorptivity of 2 specimens at 7 days and 28 days after initial curing of 28 days for each concrete mix in mm^3/mm^2/min$^{0.5}$.

Figure 3.5 : Sorptivity Test of Concrete Samples

3.4.7 Rapid Chloride-ion Permeability Test:

Rapid chloride-ion permeability test is a very fast method to determine durability of concrete. In this test, durability of concrete specimen is determined in terms of their electrical conductance. Rapid chloride-ion permeability test was evaluated as per the procedure given in ASTM C 1202 – 97. Rapid chloride-ion permeability test was performed at 28 days on standard cylindrical specimens of 100mm diameter and 50mm height. Each specimen was prepared as per the procedure give in ASTM C 1202 – 97. Each specimen was placed in between two solutions in a standard set up, with 3% NaCl solution on one side and 0.3N NaOH solution on other side and a potential difference of 60V is applied between the two terminals. The test set up is shown in Figure 3.6. Total charge passed in Coulombs was noted down after the duration of 6 hours. Results of rapid chloride-ion permeability test were reported as average charge passed for 2 specimens at 28 days in Coulombs.

Figure 3.6 : Rapid Chloride-ion Permeability Test

TABLE 3.1 : Chloride-ion Permeability Based on Charge Passed (ASTM 1202)

Charge Passed (Coulombs)	Chloride-ion Permeability
> 4000	High
2000 – 4000	Moderate
1000- 2000	Low
100 – 1000	Very Low
< 100	Negligible

3.4.8 X-ray Diffraction (XRD):

X-ray diffraction is a technique to know about the various changes in cement phases qualitatively as well as quantitatively, when any new material is introduced as replacement of cement and fine aggregate. The basic idea is to find out the effect of addition of a new material as partial replacement of cement or fine aggregate on hydration of cement. For X-ray diffraction testing, small pieces of concrete from core of cubes were collected at the time of 28 days and 90 days compressive strength testing. Cement paste was separated from coarse aggregate and it was crushed to form a fine powder. The fine powder was then sieved through a sieve of 60 micron and portion of the powder passing 60 micron was used for X-ray diffraction testing. X-ray diffraction pattern was recorded with X-ray diffractometer with CuKα radiation (λ=1.54 Å) at diffraction angle 2θ ranged between 10° to 80° in steps of 2θ=0.013°. Different phase present in the cement paste at 28 days and 90 days were identified analysing the peaks of X-ray diffraction patterns with the help of “X’Pert HighScore Plus” software tool.

3.4.9 Scanning Electron Microscope (SEM):

Scanning Electron Microscope (SEM) technique was used to study various microstructural changes occurred in the concrete, using quarry dust as partial replacement of concrete. For Scanning Electron Microscope (SEM) testing, small pieces of concrete from core of cubes were collected at the time of 28 days and 90 days compressive strength testing. These pieces of concrete are analysed at different magnifications to study the microstructure of each concrete mix at 28 days and 90 days.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 General:

In this chapter, results of the various experimental investigations are reported and discussed. In first section, results of physical testing of cement, coarse aggregate, natural sand and quarry dust are given. For cement, physical testing included determination of fineness, standard consistency, soundness, initial and final setting time, specific gravity and compressive strength of cement mortar cubes. For coarse aggregates, sieve analysis, bulk density, specific gravity and water absorption of both 20mm and 10mm nominal size of aggregate were determined. For fine aggregate, different tests conducted were sieve analysis, silt content, bulk density, specific gravity and water absorption. For sandstone quarry dust, along with other physical testing, scanning electron microscope (SEM) analysis, energy dispersive spectra (EDS) and X-ray diffraction (XRD) were also done. In next section, mix design of M30 grade of concrete is given and mix proportioning of different concrete mixes is fixed. All-in aggregate grading of combined aggregate is also given. The natural sand was partially replaced at rate of 10%, 20%, 30%, 40% and 50% with sandstone quarry dust and various tests conducted to evaluate the effect of replacement of natural sand with sandstone quarry dust on workability, density, compressive strength, splitting tensile strength, water absorption and sorptivity and chloride-ion permeability of M30 grade of concrete. The comparison between these properties of different mixes are also presented and discussed. Scanning electron microscope (SEM) and X-ray diffraction (XRD) analysis are also discussed to study the various mineralogical as well as microstructural changes due to substitute of natural sand with sandstone quarry dust.

4.2 Properties of Raw Materials:

4.2.1 Cement:

Ordinary Portland Cement of Grade 43 (OPC 43), manufactured by UltraTech Cement Limited, was used for making all concrete mixes. The cement was free from any hard lumps and uniform in colour. Physical properties of cement are given in Table 4.1.

TABLE 4.1 : Physical Properties of Ordinary Portland Cement of 43 Grade

Physical Requirement	Test Result	Specification as per IS 8112:1989
Fineness (% retained on 90 micron sieve)	1.5	10.0 Max.
Soundness (Le-Chatlier expansion in mm)	1.0	10.0 Max.
Standard Consistency (%)	27.5	–
Setting Times (minutes)		
Initial Setting Time	165	30 Min.
Final Setting Time	237	600 Max.
Compressive Strength (MPa)		
3 days ± 1 h	26.25	23 Min.
7 days ± 2 h	36.88	33 Min.
28 days ± 4 h	48.42	43 Min.
Specific Gravity	3.14	–

4.2.2 Coarse Aggregate:

A combination of 20mm nominal size aggregate and 10mm nominal size aggregate is used as coarse aggregate concrete. Both types of coarse aggregate were locally procured and conformed to Indian Standard Specifications given in BIS 383:1970. Different physical properties of both types of coarse aggregate are given in Table 4.2

TABLE 4.2 : Physical Properties of Coarse Aggregate

Physical Property	Test Result	
	20mm Nominal Size Coarse Aggregate	10mm Nominal Size Coarse Aggregate
Specific Gravity	2.66	2.64
Water Absorption (%)	0.53	0.64
Bulk Density (kg/m^3)	1640	1590
Moisture Content	Nil	Nil

Sieve analysis results of 20mm nominal size coarse aggregate and 10mm nominal size coarse aggregate are given in Table 4.3 and Table 4.4, respectively.

TABLE 4.3 : Sieve Analysis of 20mm Coarse Aggregate

Total Weight of Sample = 10kg

Sieve Size (mm)	**Weight Retained (gm)**	**% Retained**	**Cumulative % Retained**	**% Passing**	**Limits as per BIS 383:1970**
40	0	0	0	100	100
20	208	2.08	2.08	97.92	85–100
10	8904	89.04	91.12	8.88	0–20
4.75	820	8.2	99.32	0.68	0–5

TABLE 4.4 : Sieve Analysis of 10mm Coarse Aggregate

Total Weight of Sample = 5kg

Sieve Size (mm)	**Weight Retained (gm)**	**% Retained**	**Cumulative % Retained**	**% Passing**	**Limits as per BIS 383:1970**
12.5	0	0	0	100	100
10	264	5.28	5.28	94.72	85–100
4.75	3893	77.86	83.14	16.86	0–20
2.36	657	13.14	96.28	3.72	0–5

.

4.2.3 Fine Aggregate:

Locally procured natural sand was used in the experimental program and it was conformed to Indian Standard Specifications given in BIS 383:1970. Sandstone quarry dust was collected form a local crushing plant situated in district Mansa, Punjab. Different physical properties of natural sand and sandstone quarry dust are given in Table 4.5

TABLE 4.5 : Physical Properties of Fine Aggregate

Physical Property.	Test result	
	Natural Sand	**Sandstone Quarry Dust**
Specific Gravity	2.57	2.60
Water Absorption (%)	1.21	3.2
Bulk Density (kg/m^3)	1430	1490
Fineness Modulus	2.78	2.82
Silt Content (%)	0.5	6.8
Grading Zone	Zone II	Zone II
Moisture Content	Nil	Nil

Table 4.6 and Table 4.7 give sieve analysis results of natural sand and sandstone quarry dust, respectively.

TABLE 4.6 : Sieve Analysis of Natural Sand

Total Weight of Sample = 1000g

Sieve Size	Weight Retained (gm)	% Retained	Cumulative % Retained	% Passing	Limits for Zone II as per BIS 383:1970
10mm	0	0	0	100	100
4.75mm	13	1.3	1.3	98.7	90–100
2.36mm	1	0.1	1.4	98.6	75–100
1.18mm	385	38.5	39.9	60.1	55–90
600 micron	169	16.9	56.8	43.2	35–59
300 micron	267	26.7	83.5	16.5	8–30
150 micron	120	12	95.5	4.5	0–10

TABLE 4.7 : Sieve Analysis of Sandstone Quarry Dust

Total Weight of Sample = 1000g

Sieve Size	Weight Retained (gm)	% Retained	Cumulative % Retained	% Passing	Limits for Zone II as per BIS 383:1970
10mm	0	0	0	100	100
4.75mm	66	6.6	6.6	93.4	90–100
2.36mm	105	10.5	17.1	82.9	75–100
1.18mm	247	24.7	41.8	58.2	55–90
600 micron	118	11.8	53.6	46.4	35–59
300 micron	226	22.6	76.2	23.8	8–30
150 micron	101	10.1	86.3	13.7	0–20

Comparing the properties of sandstone quarry dust with natural sand, it can be observed that although specific gravity of sandstone quarry dust is slightly higher than that of sand, but it has much higher micro-fine content and water absorption as compared to natural sand. Both, natural sand and sandstone quarry dust confirm to Zone II specifications given in Indian Standard BIS 383:1970. Fig. 4.1 shows the comparison between the particle size distribution of natural sand and sandstone quarry dust.

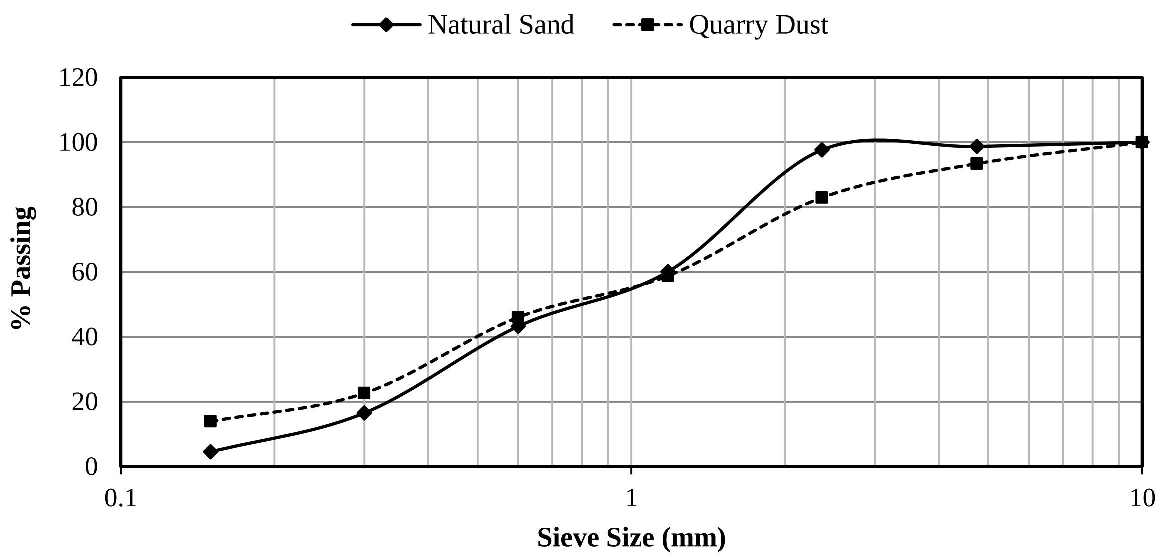

Fig. 4.1 : Comparison of Particle Size Distribution of Natural Sand and Sandstone Quarry Dust

X-ray diffraction (XRD) technique was used for the identification of various minerals present in sandstone quarry dust. XRD pattern was recorded with X-ray diffractometer at diffraction angle 2θ ranged between 10° to 80° with CuKα radiation (λ=1.54 Å) in steps of 2θ=0.013°. X-ray diffractogram of sandstone quarry dust is given in Fig. 4.2.

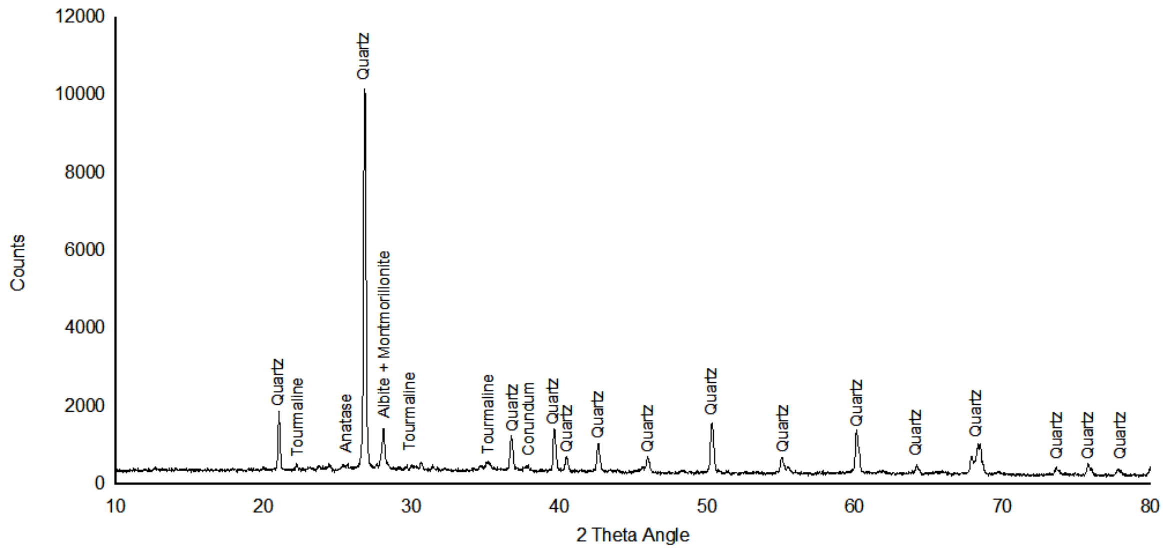

Figure 4.2 : X-ray Diffractogram of Sandstone Quarry Dust

It can be observed that sandstone quarry dust is mainly composed of quartz (SiO_2). Sandstone quarry dust is also composed of albite ($NaAlSi_3O_8$), which belongs to plagioclase feldspar group, montmorillonite (Aluminium Hydroxide Silicate), which belongs to phyllosilicate group of minerals and tourmaline, which is a crystalline boron silicate mineral. Quarry dust also contains some traces of corundum and anatase. Corundum is a crystalline form of aluminium oxide (Al_2O_3) and anatase is a form of titanium oxide (TiO_2).

To know the particle shape and surface texture of sandstone quarry dust particles, Scanning Electron Microscope (SEM) technique was used. SEM morphology of sandstone quarry dust is given in Fig. 4.3.

From Fig. 4.3, it can be observed that sandstone quarry dust particles have angular shape and rough surface texture. Along with several other properties, these two characteristics of quarry dust are different from natural sand. These characteristics are going to have a strong influence on fresh and mechanical properties of concrete.

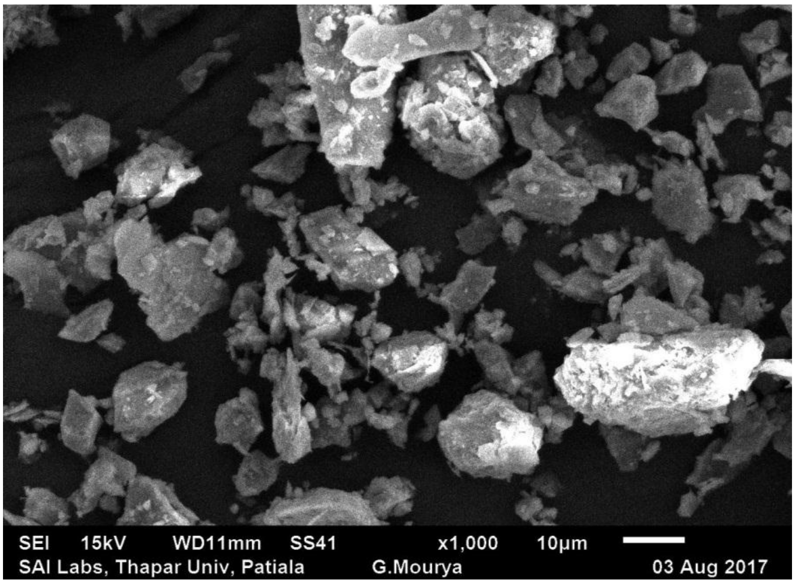

Fig. 4.3 : SEM morphology of Sandstone Quarry Dust

Energy Dispersive Spectra (EDS) analysis was done so as to find out various elements present in sandstone quarry dust as well as to find out approximate chemical composition of sandstone quarry dust. Energy Dispersive Spectrum of sandstone quarry dust is given in Figure 4.4.

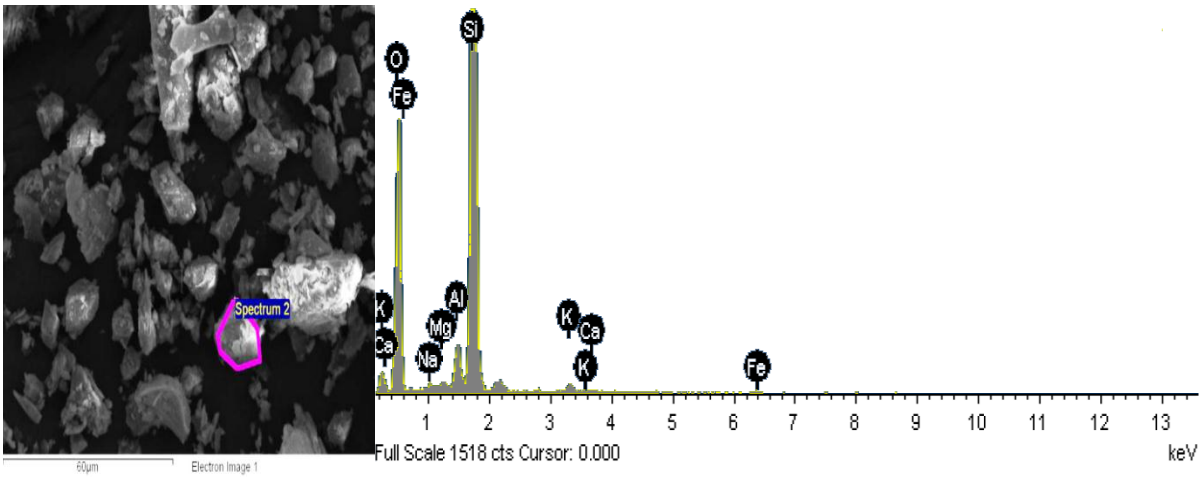

Figure 4.4 : Energy Dispersive Spectrum (EDS) of Sandstone Quarry Dust

It can be observed that various elements present in quarry dust are silicon, aluminium, iron, calcium, magnesium, sodium, potassium and oxygen. Based on EDS analysis, approximate chemical composition of quarry dust is given in Table 4.8.

TABLE 4.8
Approximate Chemical Composition of Sandstone Quarry Dust

Compound	Composition (%)
SiO_2	89.97
Al_2O_3	4.27
Fe_2O_3	2.73
CaO	0.37
MgO	0.44
Na_2O	0.59
K_2O	1.64

4.3 Mix Proportioning of Concrete:

4.3.1 All-In Aggregate Grading:

Based on the individual sieve analysis of coarse aggregate and fine aggregate, all-in aggregate grading was done as per the specifications of BIS 383:1970, so as to fix their proportions during the mix design of concrete. All-In aggregate grading, as per the proportions taken in mix design, is given in Table 4.9 and Fig. 4.5.

TABLE 4.9 : All-In Aggregate Grading

Sieve Size	Individual % Passing			Combined Aggregate % Passing			All-In Aggregate % Passing	Limits as per IS 383:1970
	20mm	10mm	Sand	20mm 39%	10mm 26%	Sand 35%		
40mm	100	100	100	39	26	35	100	100
20mm	97.92	100	100	38.19	26	35	99.19	95–100
4.75mm	0.68	16.86	98.7	0.27	4.38	34.55	39.20	30–50
600 micron	–	–	43.2	–	–	15.12	15.12	10–35
150 micron	–	–	4.5	–	–	1.58	1.58	0–6

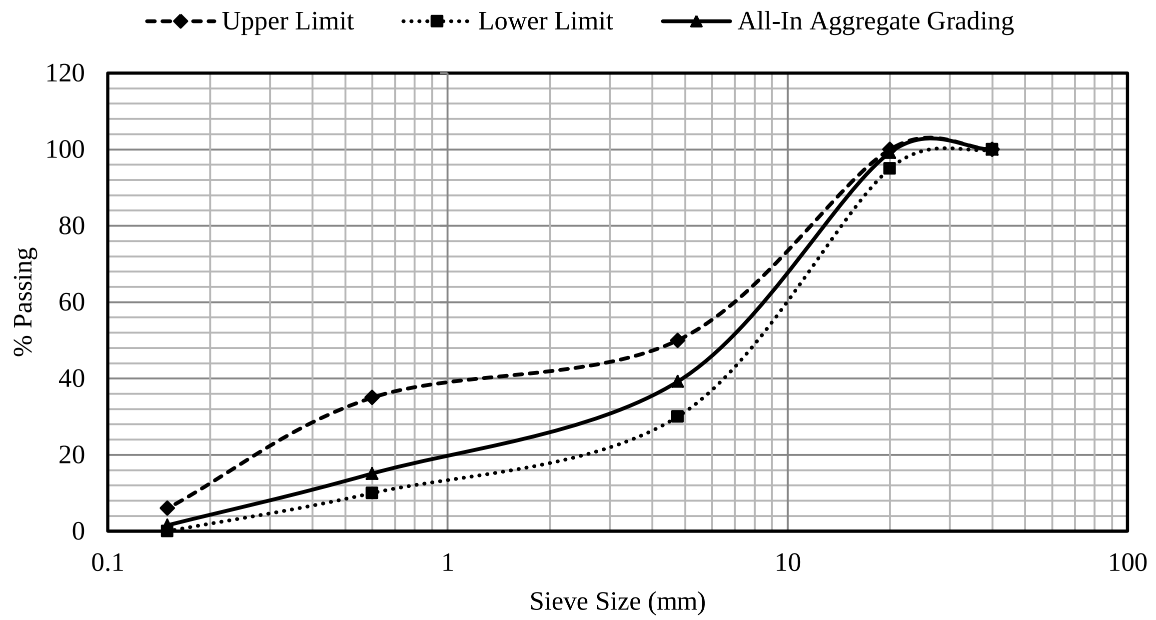

Fig. 4.5 : All-In Aggregate Grading for Concrete

Summary of the mix proportions of aggregate used in mix design of control concrete, as per the all-in aggregate grading is given in Fig. 4.6.

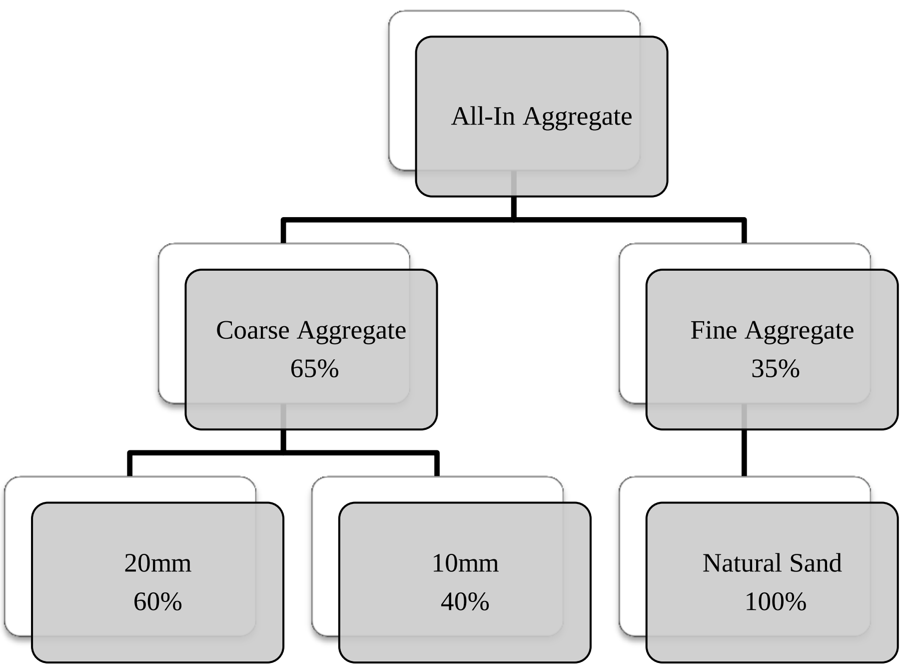

Figure 4.6 : Mix Proportioning of Aggregate as per All-In Aggregate Grading

4.3.2 Mix Design of Concrete:

Mix design of concrete used in the experimental program was as per Indian Standard Specifications given in BIS 10262:2009. Grade of the concrete selected was M30. Exposure conditions were selected as per the specifications of BIS 456:2000.

Step-1: General Stipulations for Mix Proportioning:

Grade of Concrete	:	M30
Type of Cement	:	OPC 43 grade conforming to BIS 8112
Maximum Nominal Size of Aggregate	:	20mm
Exposure Conditions	:	Moderate (for RCC)
Target Slump	:	100mm

Step 2: Target Strength for Mix Proportioning:

Assume, Standard Deviation, s = 4 MPa

Target Mean Strength at 28 days, f_t $= f_{ck} + 1.65 \times s$

$= 30 + 1.65 \times 4 = 36.6$ MPa

Step 3: Selection of Water-Cement Ratio:

As per Table 5 of IS 456:2000, maximum water-cement ratio for moderate exposure conditions in RCC = 0.5

For M30 grade of concrete, adopted water-cement ratio = 0.46

Step 4: Selection of Water Content:

As per Table 2 of IS 10262:2009, maximum water content for concrete with 20mm nominal size aggregate with slump range of 25 to 50mm = 186 kg/m^3

Estimated water content for 100mm slump = 186 + (186×6)/100 = 197.16 kg.m^3

Step 5: Calculation of Cement Content:

Water-cement ratio = 0.46

Cement Content = 197.16/0.46 = 428.6 kg/m^3 ≈ 430 kg/m^3

As per Table 5 of IS 456:2000, for moderate exposure conditions in RCC, minimum cement content = 300 kg/m^3, Hence OK

Step 6: Proportions of Volume of Coarse Aggregate and Fine Aggregate:

As per all-in aggregate grading:

Volume of Fine Aggregate = 35%

Volume of Coarse Aggregate = 65%

20mm : 10mm = 60 : 40

Thus, Volume of 20mm nominal size aggregate = $0.65 \times 0.6 = 0.39$

Volume of 10mm nominal size aggregate = $0.65 \times 0.4 = 0.26$

Step 7: Mix Calculations:

The mix calculations for unit volume of concrete are given below:

Volume of Cement = $430/(3.14 \times 1000) = 0.1369\ m^3$

Volume of Cement = $197.8/(1 \times 1000) = 0.1978\ m^3$

Volume of all-in aggregate = $1 - (0.1369+0.1978) = 0.6653\ m^3$

Mass of sand = $0.6653 \times 0.35 \times 2.57 \times 1000 = 598.44\ kg/m^3 \approx 600\ kg/m^3$

Mass of 20mm aggregate = $0.6653 \times 0.39 \times 2.66 \times 1000 = 690.18\ kg/m^3 \approx 690\ kg/m^3$

Mass of 10mm aggregate = $0.6653 \times 0.26 \times 2.64 \times 1000 = 456.66\ kg/m^3 \approx 457\ kg/m^3$

Step 8: Mix Proportioning for Control Concrete:

Summary of mix proportioning of control concrete with all aggregate in SSD conditions is given below:

Cement	=	430 kg/m^3
Water	=	197.8 kg/m^3
Fine Aggregate	=	600 kg/m^3
20mm nominal size Coarse Aggregate	=	690 kg/m^3
10mm nominal size Coarse Aggregate	=	457 kg/m^3
Water-cement ratio	=	0.46

4.3.3 Mix Proportioning of Different Concrete Mixes:

Table 4.10 gives a summary of mix proportioning of different concrete mixes with all aggregate in SSD condition. Control concrete is denoted as CM, whereas, concrete mixes made with replacing natural sand with sandstone quarry dust at a replacement level of 10%, 20%, 30%, 40% and 50% are denoted as QD10, QD20, QD30, QD40 and QD50, respectively.

TABLE 4.10 : Mix Proportioning of Concrete Mixes with Aggregate in SSD Condition

Mix Designation	Cement (kg/m^3)	w/c	Water Content (kg/m^3)	Natural Sand (kg/m^3)	Sandstone Quarry Dust (kg/m^3)	Coarse Aggregate (kg/m^3)	
						20mm	10mm
CM	430	0.46	197.8	600	0	690	457
QD10	430	0.46	197.8	540	60	690	457
QD20	430	0.46	197.8	480	120	690	457
QD30	430	0.46	197.8	420	180	690	457
QD40	430	0.46	197.8	360	240	690	457
QD50	430	0.46	197.8	300	300	690	457

4.3.4 Water Correction:

As the quantity of aggregate calculated in mix design of concrete was based upon the SSD condition of aggregate, so necessary water corrections must be applied, as all aggregate used were in dry conditions. Water corrections applied at the time of casting are given as follows:

Water correction for Sand = $600 \times 1.21/100 = 7.26$ kg/m^3

Water correction for 20mm nominal size aggregate = $690 \times 0.53/100 = 3.66$ kg/m^3

Water correction for 10mm nominal size aggregate = $457 \times 0.64/100 = 2.92$ kg/m^3

Water correction in water content = $7.26+3.66+2.92 = 13.84$ kg/m^3

Summary of mix proportioning of control concrete with all aggregate in dry conditions is given below:

Water	=	197.8 + 13.84	=	211.64 kg/m^3
Fine Aggregate	=	600 − 7.26	=	592.74 kg/m^3
20mm nominal size Coarse Aggregate	=	690 − 3.66	=	686.34 kg/m^3
10mm nominal size Coarse Aggregate	=	457 − 2.92	=	454.08 kg/m^3

For concrete mixes containing sandstone quarry dust, water correction for 20mm and 10mm nominal size aggregate will remain same. However, for natural sand and quarry dust, it is different for different concrete mixes, according to the weight of natural sand and quarry dust in that particular mix. For instance, water correction calculation for QD10 is as follows:

Water correction for Sand = $540 \times 1.21/100$ = 6.53 kg/m^3

Water correction for 20mm nominal size aggregate = $690 \times 0.53/100$ = 3.66 kg/m^3

Water correction for 10mm nominal size aggregate = $457 \times 0.64/100$ = 2.92 kg/m^3

Water correction for quarry dust = $60 \times 3.2/100$ = 1.92 kg/m^3

Water correction in water content = 6.53+3.66+2.92+1.92 = 15.03 kg/m^3

Summary of mix proportioning of QD10 concrete mix with all aggregate in dry conditions is given below:

Water	=	197.8 + 15.03	=	212.83 kg/m^3
Fine Aggregate	=	540 − 6.53	=	533.47 kg/m^3
Quarry Dust	=	60 − 1.92	=	58.08 kg/m^3
20mm nominal size Coarse Aggregate	=	690 − 3.66	=	686.34 kg/m^3
10mm nominal size Coarse Aggregate	=	457 − 2.92	=	454.08 kg/m^3

Similarly, mix proportioning of QD20, QD30, QD40 and QD50 are also calculated with all aggregate in dry conditions. Table 4.11 gives a summary of mix proportioning of different concrete mixes with all aggregate in SSD condition.

TABLE 4.11 : Mix Proportioning of Concrete Mixes with Aggregate in Dry Condition

Mix Designation	**Cement (kg/m^3)**	**w/c**	**Water Content (kg/m^3)**	**Natural Sand (kg/m^3)**	**Sandstone Quarry Dust (kg/m^3)**	**Coarse Aggregate (kg/m^3)**	
						20mm	**10mm**
CM	430	0.46	211.64	592.74	0	686.34	454.08
QD10	430	0.46	212.83	533.47	58.08	686.34	454.08
QD20	430	0.46	214.03	474.19	116.16	686.34	454.08
QD30	430	0.46	215.22	414.92	174.24	686.34	454.08
QD40	430	0.46	216.42	355.64	232.32	686.34	454.08
QD50	430	0.46	217.61	296.37	290.40	686.34	454.08

4.4 Fresh Properties of Concrete:

4.4.1 Workability:

Workability of all concrete mixes was evaluated as slump in mm, to study the effect of replacement of natural sand with sandstone quarry dust on workability of concrete and the observations are given in Table 4.12.

TABLE 4.12 : Slump Test Results of Fresh Concrete Mixes

Mix Designation	**Slump (mm)**
CM	90
QD10	85
QD20	80
QD30	75
QD40	65
QD50	50

Observations of workability of all concrete mixes as slump in mm are graphically represented in Figure 4.7.

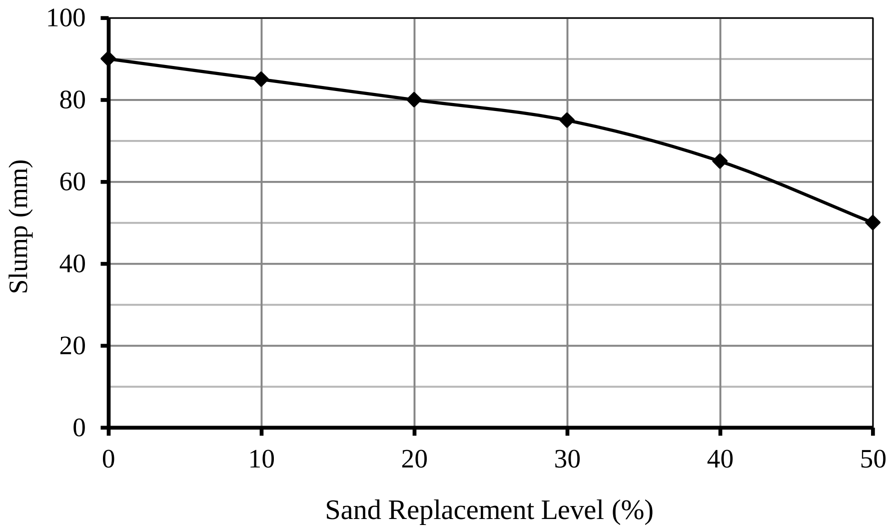

Figure 4.7 : Effect of Replacement of Natural Sand with Sandstone Quarry Dust on Workability of Concrete

It can be observed that slump of all concrete mixes with sandstone quarry dust was lesser than that of control concrete. With the addition of sandstone quarry dust as a partial substitute of natural sand, workability of concrete goes on decreasing and the decrease in workability is more profound at higher replacement levels of 40% and 50%. The slump of control mix was 90mm, whereas for concrete mix with 50% quarry dust, slump dropped to 50mm. Similar kind of decreasing trend of workability due to addition of quarry dust as partial substitute of natural sand is also reported in previous researches by Shi-Cong and Chi-Sun (2009), Vijayalakshmi et. al. (2013) and Singh et. al. (2016).

The decrease in workability due to the addition of sandstone quarry dust as partial substitute of natural sand can be attributed to the difference in particle size distribution and shape of natural sand and sandstone quarry dust particles. Fig. 4.1 gives the difference between particle size distribution of natural sand and sandstone quarry dust. Silt content in natural sand was 0.5%, however, quarry dust has a silt content of 6.8%. Moreover, SEM images show that sandstone quarry dust particle has angular shape with rough surface texture, whereas natural sand generally has round particles with smooth surface texture. Thus, when the natural sand was replaced with equal weight of sandstone quarry dust, specific surface area was increased due to the presence of excessive micro-fines in sandstone quarry dust as compared to natural sand. The angular shape of sandstone quarry dust particles further enhanced the water demand of concrete, which leads to decrease in workability. Moreover, sandstone quarry dust particles have rough surface texture, which tend to increase the friction between paste and coarse aggregate and may also be reason of decrease of workability of concrete.

It must be noted that slump of all concrete mixes lies in the range of 50-100mm, which is medium degree of workability as per Indian Standard Specifications BIS 456:2000. It means that all concrete mixes may be used for the casting of heavily reinforced sections, such as slabs, beams, columns etc.

It can be concluded that inclusion of sandstone quarry dust as a partial substitute of natural sand leads to increase in water demand of concrete, i.e., higher water content will be needed to produce concrete with same workability as that of control concrete. As increase in water content will have negative impact on compressive strength, so use of superplasticizers may be one of the options, which can be used to counteract the negative influence of sandstone quarry dust inclusion on workability of concrete.

4.5 Hardened Properties of Concrete:

4.5.1 Density of Concrete:

Density of concrete, based upon the 1-day weight of the cubes of 150mm×150mm×150mm at the time of demoulding after 24 hours of casting, was calculated and observations of density of concrete with increase in substitution rate of natural sand with sandstone quarry dust are given in Table 4.13.

TABLE 4.13 : 1-day Density of Concrete Mixes

Mix Designation	Weight of Cube (g)	Average Weight of Cubes (g)	Density (kg/m^3)
CM	8156	8137.7	2411.16
	8116		
	8141		
QD10	8176	8211.7	2433.09
	8210		
	8249		
QD20	8374	8314.0	2463.41
	8261		
	8304		
QD30	8441	8384.7	2484.35
	8418		
	8295		
QD40	8509	8466.7	2508.64
	8432		
	8459		
QD50	8507	8463.0	2507.56
	8473		
	8409		

It can be observed that with the addition of sandstone quarry dust as a partial substitute of natural sand, density of the concrete is increasing. The relationship between density of concrete mixes with increase in sand substitution level is not linear, but it follows cubic variation. Concrete mix with 40% sand replacement has maximum density among all concrete mixes. Control concrete has a density of 2411.16 kg/m^3, whereas for concrete mix with 40% sand replacement, it has been increased to 2508.64 kg/m^3, which is an increase of 4%. Interestingly, density of concrete with 50% sand replacement shows a slight decrease in density, as compared to that of concrete with 40% sand replacement level.

Graphical representation of average 1-day density of different concrete mixes at various sand replacement levels is given in Fig. 4.8.

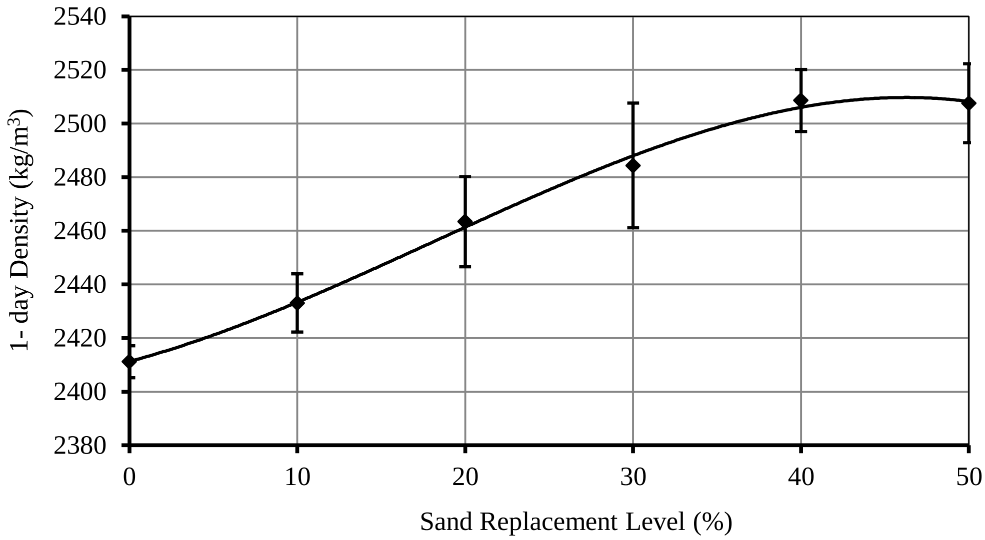

Fig. 4.8 : Effect of Replacement of Natural Sand with Sandstone Quarry Dust on 1-day Density of Concrete

The enhancement in density of concrete mixes with replacement of natural sand with sandstone quarry dust is mainly attributed to the filling effect of micro-fines present in the quarry dust, which tend to fill up the voids present in concrete and makes the microstructure of concrete more dense. Moreover, specific gravity of sandstone quarry dust is greater than that of natural sand. Thus, we are replacing natural sand with comparatively heavier particles, which may also be the reason behind the increase in density of concrete. Thus, up to 40% replacement level, density of concrete with sandstone quarry dust inclusion increases. It means that 40% sand replacement level may have optimum amount of micro-fines to fill up all the voids in concrete. So, at 50% replacement level, the concrete may now have excessive micro-fines, which instead of filling the voids, start to occupy the main body of the concrete. This may be the reason that after 40% dust replacement level, density of the concrete goes towards saturation and show a slight decreasing trend.

4.5.2 Compressive Strength:

Compressive strength of different concrete mixes was evaluated at age of 7 days, 28 days and 90 days to study the effect of partial substitution of natural sand with sandstone quarry dust and different observations are given in Table 4.14.

TABLE 4.14 : Compressive Strength Test Results of Concrete Mixes

Mix Designation	Compressive Strength (MPa)					
	7 days		28 days		90 days	
	Individual	Average	Individual	Average	Individual	Average
CM	27.94	29.77	37.00	36.13	39.04	38.49
	31.08		34.59		38.96	
	30.29		36.80		37.48	
QD10	32.87	31.24	37.13	37.67	41.03	40.57
	30.58		38.60		39.10	
	30.27		37.29		41.58	
QD20	32.35	32.78	39.52	39.43	43.98	42.58
	33.25		40.12		40.96	
	32.74		38.66		42.79	
QD30	35.13	34.22	40.41	40.80	43.15	44.74
	33.32		39.94		45.86	
	36.52		42.02		45.21	
QD40	34.57	35.44	41.11	41.83	47.94	46.96
	35.23		42.57		47.39	
	36.52		41.82		45.56	
QD50	33.36	33.91	38.64	40.55	45.94	44.65
	35.12		42.34		44.04	
	33.24		40.67		43.99	

It can be observed that inclusion of sandstone quarry dust as replacement of natural sand leads to significant enhancement in compressive strength of concrete at all ages as compared to control mix. At 7 days, compressive strength of control mix was 29.77 MPa, whereas compressive strength of QD10, QD20, QD30, QD40 and QD50 concrete mixes was 31.24, 32.78, 34.22, 35.44 and 33.91 MPa, respectively. Similarly, at 28 days, compressive strength of control mix was 36.13 MPa, whereas compressive strength of QD10, QD20, QD30, QD40 and QD50 concrete mixes was 37.67, 39.73, 40.80, 41.83 and 40.55 MPa, respectively. At 90 days, compressive strength of control mix was 38.49 MPa, whereas compressive strength QD10, QD20, QD30, QD40 and QD50 concrete mixes was 40.57, 42.58, 44.74, 46.96 and 44.65 MPa, respectively. It means that compressive strength of concrete goes on increasing with increase in sand replacement level and attains a maximum value at sand replacement level of 40% and then starts decreasing. Concrete mixes show similar trend at all ages of testing. Similar trend in compressive strength was also observed in previous researches by Shi-Cong and Chi-Sun (2009) Omar et. al. (2012), and Singh et. al. (2016).

At age of 28 days, percent increase in compressive strength of concrete for QD10, QD20, QD30, QD40 and QD50 concrete mixes as compared to control concrete was 4.3%, 9.1%, 12.9%, 15.8% and 12.2%, respectively. However, at age of 7 days, increase in compressive strength of concrete for QD10, QD20, QD30, QD40 and QD50 concrete mixes as compared to control concrete was 4.9%, 10.1%, 14.9%, 19.0% and 13.9%, respectively. At age of 90 days, increase in compressive strength of concrete for QD10, QD20, QD30, QD40 and QD50concrete mixes as compared to control concrete was 5.4%, 10.6%, 16.2%, 22.0% and 16.0%, respectively.

Graphical representation of compressive strength results of all concrete mixes at different ages is given in Fig. 4.9.

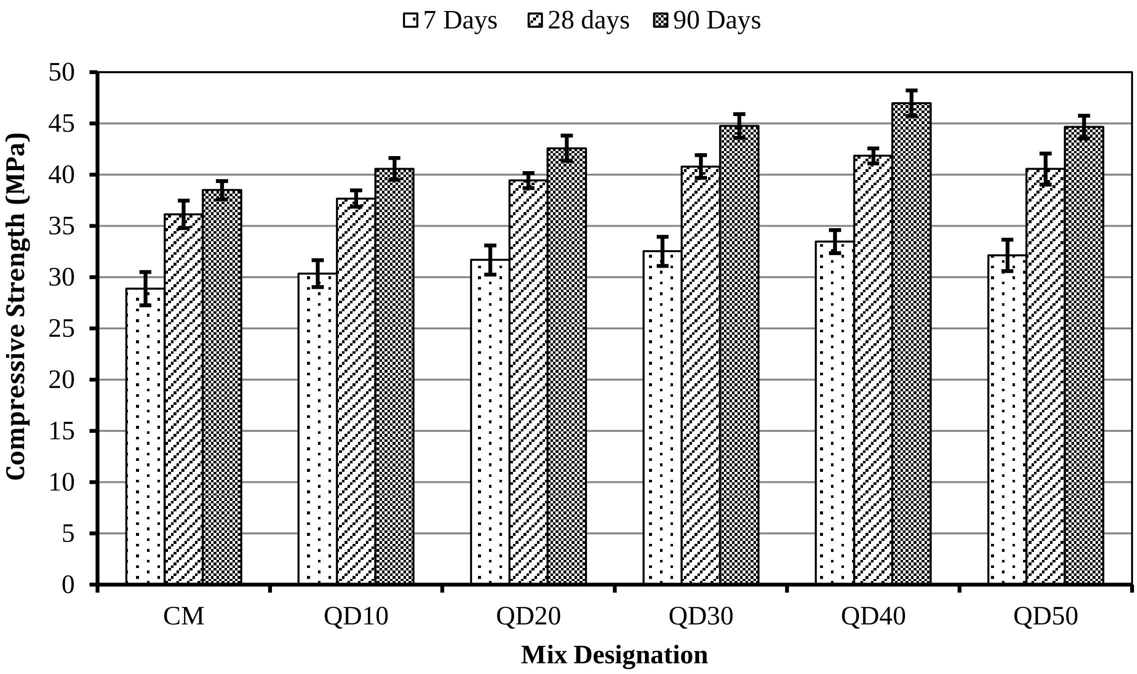

Fig. 4.9 : Effect of Replacement of Natural Sand with Sandstone Quarry Dust on Compressive Strength of Concrete

The increase in compressive strength of concrete at all ages by replacing natural sand with sandstone quarry dust may be mainly attributed to the increase in density of concrete. Regression analysis has been done to find out the relationship between 1-day density of each concrete mix with its respective compressive strengths at 7, 28 and 90 days, is shown in Fig. 4.10.

From regression analysis, it is obvious that compressive strength of concrete mixes is directly proportional to the density of concrete at all ages. Coefficient of determination, R^2, was calculated at each age and the value of R^2 for the linear variation between 1-day density of concrete and compressive strength of concrete comes out to be 0.9289, 0.9391 and 0.9387 at 7 days, 28 days and 90 days, respectively. Thus, there exists a strong correlation between density of concrete and compressive strength of concrete.

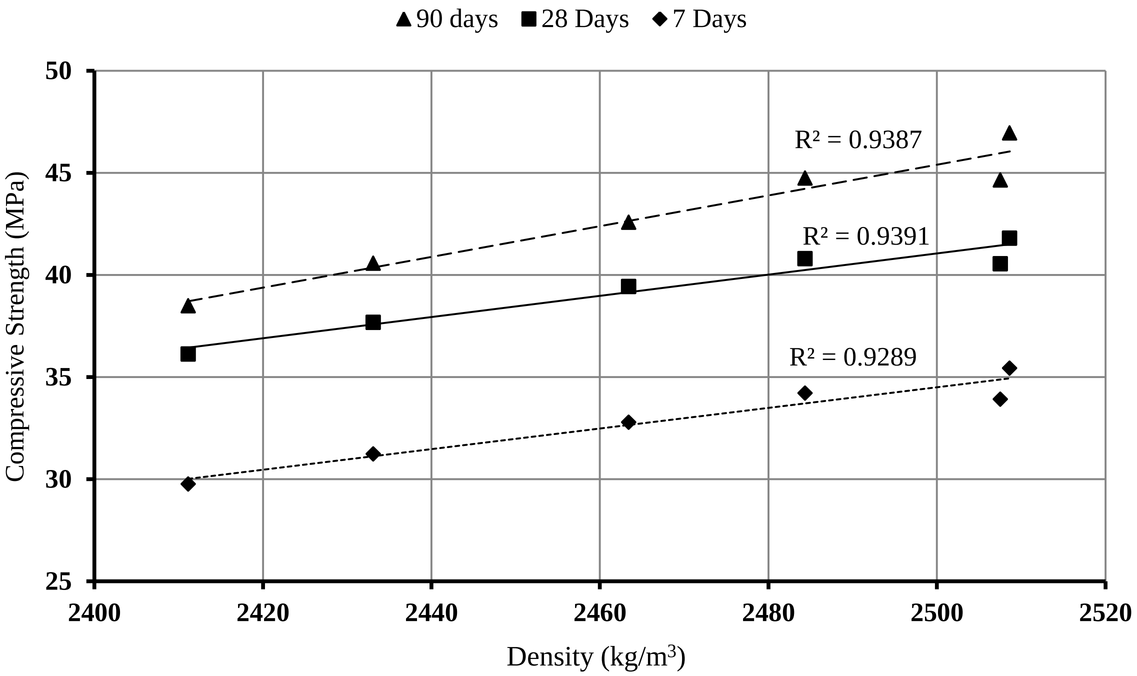

Fig. 4.10 : Relation between 1-day Density and Compressive Strength of Concrete at all Ages

The other fact is that as specific gravity of sandstone quarry dust is more than that of natural sand, intrinsic strength of quarry dust particles will be greater than that of natural sand particles, which may also be a cause of increase in compressive strength. Moreover, the inclusion of sandstone quarry dust particles may result in better bond between fine aggregate and cement paste due to the refinement of interfacial transition zone. The rough surface texture of quarry dust particle may have resulted in better bonding between the fine aggregate particles and cement paste.

One of the important observations from Table 4.14 and Figure 4.9 was that compressive strength of concrete is maximum for concrete with 40% sand replacement level and for further replacement of sand by 50%, the compressive strength starts decreasing. This decrease can be explained on the basis of two facts. First, the workability of the concrete goes on decreasing with increase in sand replacement level and for concrete mix with 50% sand replacement, slump is low, i.e., 50mm, as compared to other mixes. This decrease in workability may have an adverse influence on compressive strength of concrete leading to improper compaction. Secondly, as the quarry dust content is increasing, the amount of micro-fines present in concrete is also increasing and specific surface area of aggregate also goes on increasing. As cement content is constant for all the mixes, at higher sand replacement of 50%, cement paste becomes not enough to coat all the aggregate particles properly. Thus, at higher sand replacement level, compressive strength of the concrete starts decreasing after reaching a maximum value.

It has also been observed that rate of increase in compressive strength as compared to control mix is more at 7 days and 90 days, as compared to that of at 28 days. For instance, in QD40 concrete mix, rate of increase in compressive strength as compared to control mix at 7 days and 90 days was 19.0% and 22.0%, respectively. However, rate of increase in compressive strength for the same concrete mix at 28 days was 15.8%. Such trend is more profound in concrete mixes with higher replacement levels of 30%, 40% and 50%. Bonavetti and Irassar (1994) and Vijayalakshmi et. al. (2013) also reported higher rate of increase in compressive strength at early ages in mortar and concrete, respectively.

Higher rate of increase in compressive strength at early age can be explained on the basis of accelerated cement hydration due to the presence of rock dust micro-fines. These micro-fines present in quarry dust acts as nucleation sites to accelerate the process of cement hydration and promote the formation of hydration products at early ages, especially tricalcium aluminate (C_3A). Donza et. al. (2002), Beixing et. al. (2009) and Vijayalakshmi et. al. (2013) also reported nucleation effect of rock-fines, which lead to increase in compressive strength at early ages. That’s why rate of increase in 7 days compressive strength is more as compared to rate of increase in 28 days strength in all concrete mixes. At later ages, quarry dust micro-fines may have provided better conditions for hydration of cement due to larger surface area. Moreover, due to the irregular cavities present in quarry dust particles, they initially absorb water, which they may have released at later ages. This process may have resulted in continuous hydration of cement with age. So rate of increase in compressive strength at 90 days is also higher.

It can be concluded that concrete mix with 40% sand replacement has maximum compressive strength at all ages. So mix of 40% sandstone quarry dust and 60% natural sand can be regarded as optimum combination to achieve maximum compressive strength.

4.5.3 Splitting Tensile Strength:

Splitting tensile strength of different concrete mixes was evaluated at age of 7 days, 28 days and 90 days to study the effect of partial substitution of natural sand with sandstone quarry dust and observations are given in Table 4.15.

TABLE 4.15 : Splitting Tensile Strength Test Results of Concrete Mixes

Mix Designation	Splitting Tensile Strength(MPa)					
	7 days		28 days		90 days	
	Individual	Average	Individual	Average	Individual	Average
CM	2.47	2.41	2.65	2.78	2.91	2.86
	2.37		2.77		2.76	
	2.39		2.93		2.91	
QD10	2.38	2.47	2.76	2.82	3.00	2.95
	2.50		2.87		2.96	
	2.54		2.84		2.87	
QD20	2.68	2.59	2.92	2.96	3.12	3.13
	2.51		2.87		3.09	
	2.57		3.08		3.19	
QD30	2.94	2.88	3.17	3.25	3.43	3.43
	2.92		3.28		3.37	
	2.78		3.31		3.50	
QD40	3.08	3.02	3.33	3.39	3.62	3.59
	2.98		3.39		3.53	
	3.00		3.45		3.61	
QD50	2.71	2.84	3.28	3.22	3.45	3.45
	2.95		3.30		3.35	
	2.85		3.07		3.55	

It can be observed that inclusion of sandstone quarry dust as replacement of natural sand leads to significant enhancement in splitting tensile strength of concrete as compared to control mix at all ages. At 7 days, splitting tensile strength of control mix was 2.41 MPa, whereas splitting tensile strength of QD10, QD20, QD30, QD40 and QD50 concrete mixes was 2.47, 2.59, 2.88, 3.02 and 2.84 MPa, respectively. Similarly, at 28 days, splitting tensile of control mix was 2.78 MPa, whereas splitting tensile strength of QD10, QD20, QD30, QD40 and QD50 concrete mixes was 2.82, 2.96, 3.25, 3.39 and 3.22 MPa, respectively. At 90 days, splitting tensile strength of control mix was 2.86 MPa, whereas splitting tensile strength of QD10, QD20, QD30, QD40 and QD50 concrete mixes was 2.95, 3.13, 3.43, 3.59 and 3.45 MPa, respectively. It means that splitting tensile strength of concrete goes on increasing with increase in sand substitution rate and attains a maximum value at sand replacement level of

40% and then starts decreasing. Concrete mixes show similar trend at all ages of testing. Similar trend in splitting tensile strength was also observed by Ghannam et. al (2016).

At age of 28 days, increase in splitting tensile strength of concrete for QD10, QD20, QD30, QD40 and QD50 concrete mixes as compared to control concrete was 1.4%, 6.5%, 16.9%, 21.9% and 15.8%, respectively. However, at age of 7 days, increase in splitting tensile strength of concrete for QD10, QD20, QD30, QD40 and QD50 concrete mixes as compared to control concrete was 2.5%, 7.5%, 19.5%, 25.3% and 17.8%, respectively. At age of 90 days, increase in splitting tensile strength of concrete for QD10, QD20, QD30, QD40 and QD50 concrete mixes as compared to control concrete was 3.1%, 9.4%, 19.9%, 25.5% and 20.6%, respectively.

Graphical representation of splitting tensile strength results of all concrete mixes at different ages is given in Fig. 4.11.

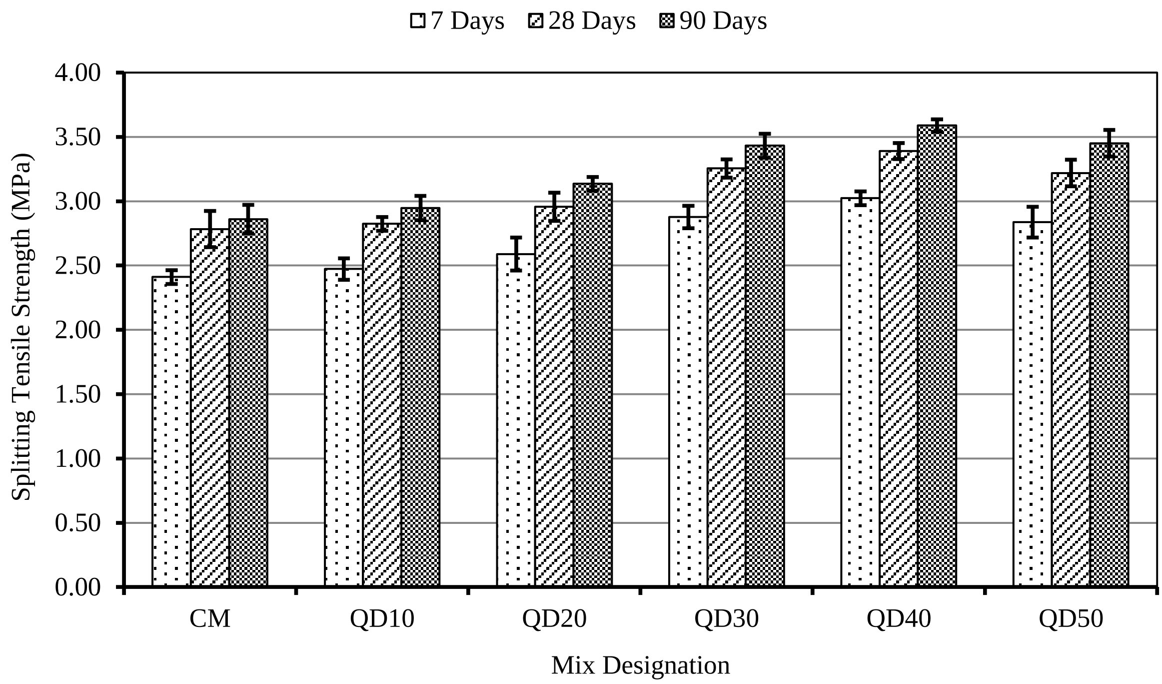

Figure 4.11 : Effect of Replacement of Natural Sand with Sandstone Quarry Dust on Splitting Tensile Strength of Concrete

The increase in splitting tensile of concrete at all ages by replacing natural sand with sandstone quarry dust may be mainly attributed to the increase in density of concrete, as explained in the case of compressive strength. Regression analysis has been done to find out the relationship between 1-day density of each concrete mix with its respective splitting tensile strength of concrete mixtures at 7, 28 and 90 days, is shown in Fig. 4.12.

From regression analysis, it is clear that splitting tensile strength of concrete mixes is directly proportional to the density of concrete at all ages. Coefficient of determination, R^2, was calculated at each age and the value of R^2 for the linear variation between 1-day density of concrete and splitting tensile strength of concrete comes out to be 0.8959, 0.9013 and 0.95 at 7 days, 28 days and 90 days, respectively. Thus, there exists a good correlation between density of concrete and splitting tensile strength of concrete at 7 days and 28 days, whereas correlation is strong for splitting tensile strength at 90 days. Similar arguments as that of in case of compressive strength can be made in this case also to explain the increase in splitting tensile strength with increase in sand substitution rate.

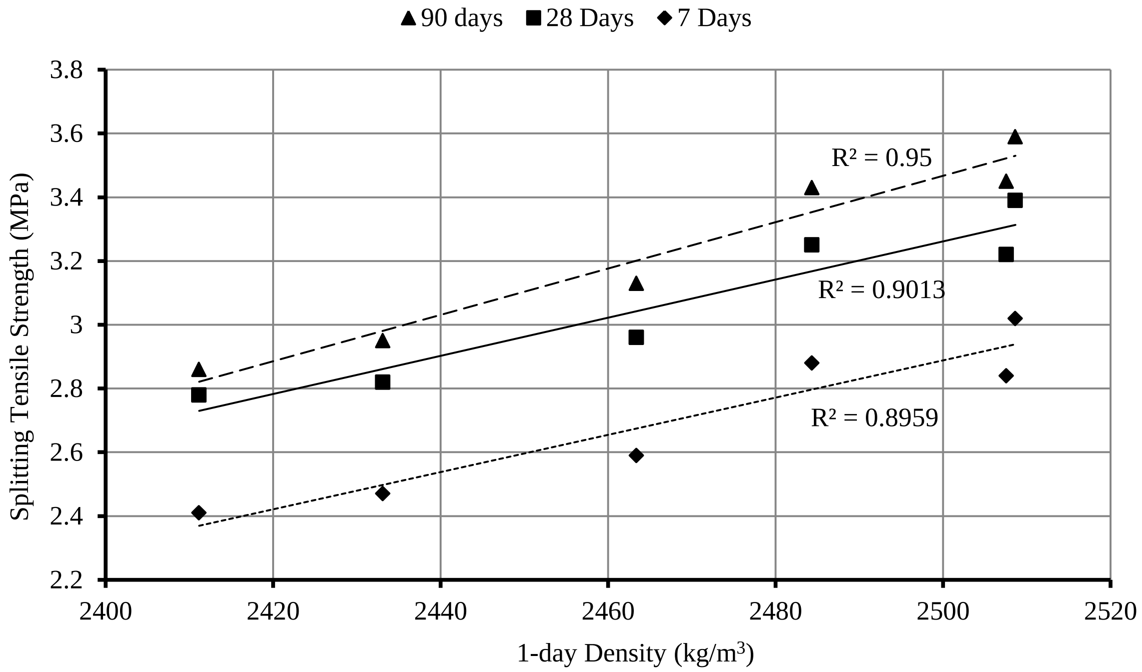

Figure 4.12 : Relation between 1-day Density and Splitting Tensile Strength of Concrete at All Ages

One of the important observations from Table 4.15 and Fig. 4.12 was that splitting tensile strength of concrete is maximum for concrete with 40% sand replacement level and for further replacement of sand by 50%, the splitting tensile strength starts decreasing, at all ages of testing. This variation is same as that was in case of compressive strength. Similar arguments can be made to explain this behaviour as in case of compressive strength.

It has also been observed that rate of increase in splitting tensile strength as compared to control mix is more at 7 days and 90 days, as compared to that of at 28 days. For instance, in QD40 concrete mix, rate of increase in splitting tensile strength as compared to control mix at 7 days and 90 days was 25.3% and 25.5%, respectively. However, rate of increase in splitting tensile strength for the same concrete mix at 28 days was 21.9%. Such trend is more profound in concrete mixes with higher replacement levels of 30%, 40% and 50%. This trend is same as observed in the case of compressive strength of concrete mixes. Similar arguments can be made in this case also, as that of in compressive strength.

It should also be noted that percent increase in splitting tensile strength of concrete is much higher as compared to percent increase in compressive strength. For optimum sand replacement of 40%, increase in compressive strength at 7, 28 and 90 days was 19.0%, 15.8% and 22.0%, respectively, whereas increase in splitting tensile strength at 7, 28 and 90 days was 25.3%, 21.9% and 25.5%, respectively. Thus effect of partial substitution of natural sand by sandstone quarry dust is more significant for splitting tensile strength.

It can be concluded that concrete mix with 40% sand replacement has maximum splitting tensile strength at all ages. So mix of 40% sandstone quarry dust and 60% natural sand can be regarded as optimum combination to achieve maximum splitting tensile strength.

4.5.4 Relationship between Splitting Tensile Strength and Compressive Strength:

Ratios of splitting tensile strength to compressive strength of concrete as % are given in Table 4.16.

TABLE 4.16 : Splitting Tensile Strength and Compressive Strength Ratios at Different Ages

Mix Notation	**Splitting Tensile Strength and Compressive Strength Ratio (%)**		
	7 Days	**28 Days**	**90 days**
CM	8.10	7.69	7.43
QD10	7.91	7.49	7.27
QD20	7.90	7.51	7.35
QD30	8.42	7.97	7.67
QD40	8.52	8.10	7.64
QD50	8.38	7.94	7.73

Careful observation of Table 4.16 shows that there is no definite relationship between the strength ratios and sand replacement level. Average ratio of splitting tensile strength and compressive strength of concrete comes out to be 8.20, 7.78 and 7.52 at 7 days, 28 days and 90 days, respectively. Thus, with age, ratio between splitting tensile strength and compressive strength is decreasing.

Regression analysis may be used to find out the relation between compressive strength and splitting tensile strength. Figure 4.13 demonstrates the relationship between splitting tensile strength and compressive strength of concrete made by replacing natural sand with sandstone quarry dust.

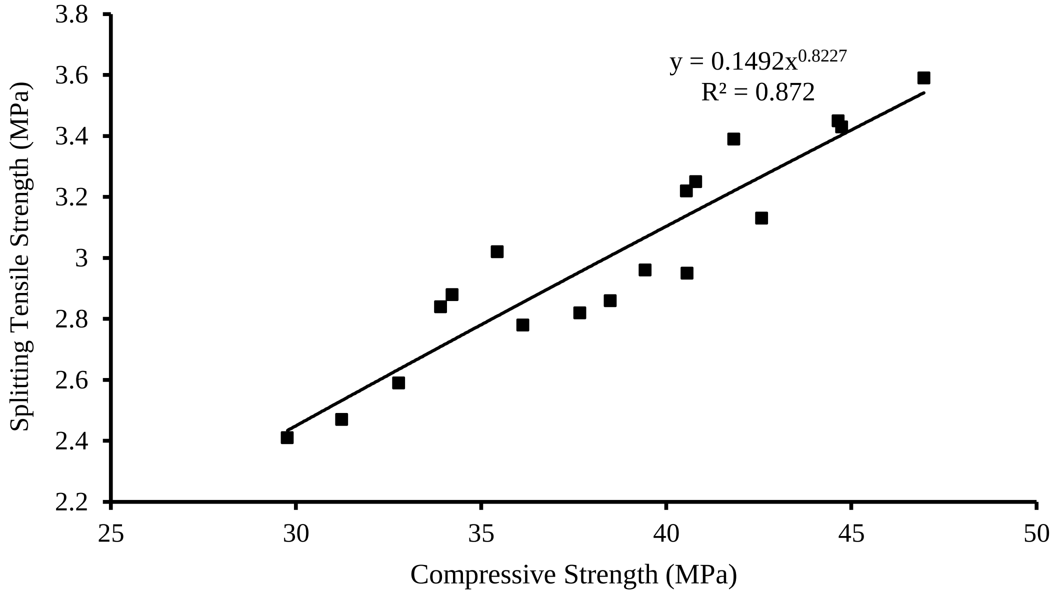

Figure 4.13 : Relation between Splitting tensile Strength and Compressive Strength of Sandstone Quarry Dust Concrete

The equation showing the relationship between compressive strength and splitting tensile strength of concrete along with coefficient of determination is given below:

$$\mathbf{f_{st} = 0.1492\,(f_{cu})^{0.8227} \quad , \quad R^2 = 0.872}$$

where,

f_{st} = Splitting tensile strength in MPa

f_{cu} = Compressive strength of cube in MPa

Higher value of coefficient of determination, R^2, indicates that there is a good correlation between data points and regression curve.

To check the accuracy of the relation between splitting tensile strength and compressive strength, the proposed equation is compared with the relationships given in standard literatures. The empirical formulas to find out splitting tensile strength from compressive strength of concrete as per ACI 318M-14 and CEB-FIP Model Code, 2010 is given in equation 1 and 2, respectively:

$$f_{st} = 0.56\,(f_{cy})^{0.5} \qquad (1)$$

$$f_{st} = 0.3\,(f_{cy})^{2/3} \qquad (2)$$

where,

f_{st} = Splitting tensile strength in MPa

f_{cy} = Compressive strength of cylinder in MPa, which may be taken as 0.8 f_{cu}

The comparison between the equation proposed by present study and the equations given by ACI 318-14 and CEB-FIP Model Code, 2010 is demonstrated in Figure 4.14.

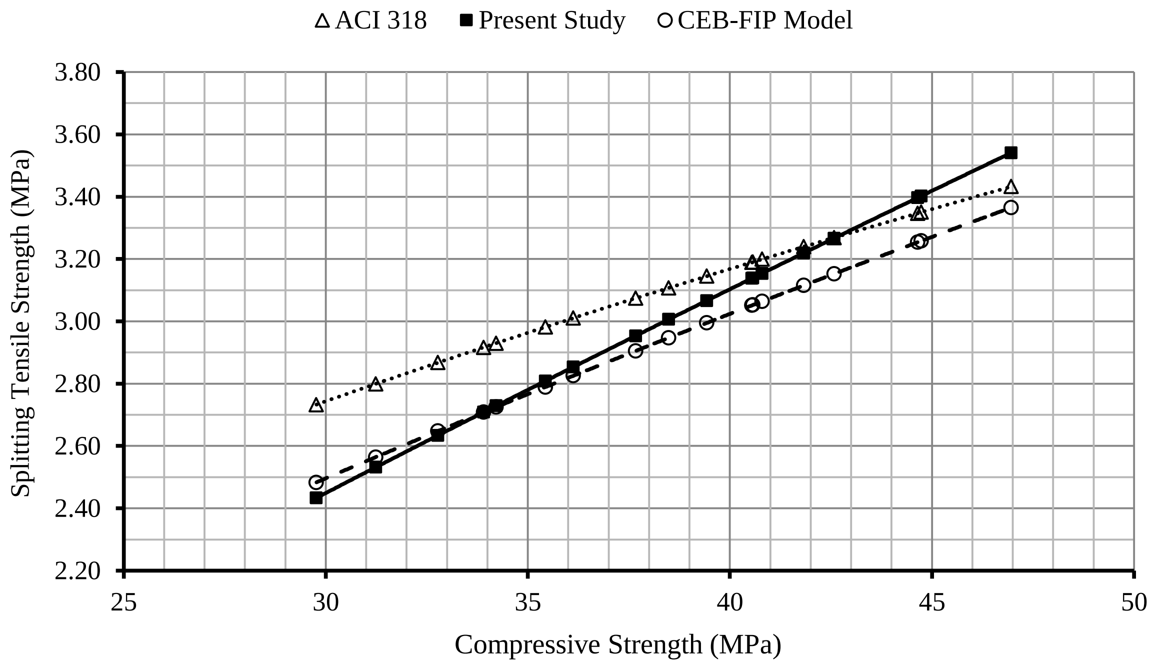

Figure 4.14 : Comparison between Equation Proposed by Present Study and Relations given in Other Standard Literatures

From Figure 4.14, it is clear that the relationship obtained between compressive strength and splitting tensile strength is very close to the equation given in other standard literatures. To have better idea, regression analysis is done between the splitting tensile strength values obtained from the equation proposed by the present study and the splitting tensile strength values obtained from relations given in ACI 318-14 and CEB-FIP Model Code, 2010, which is shown in Fig. 4.15.

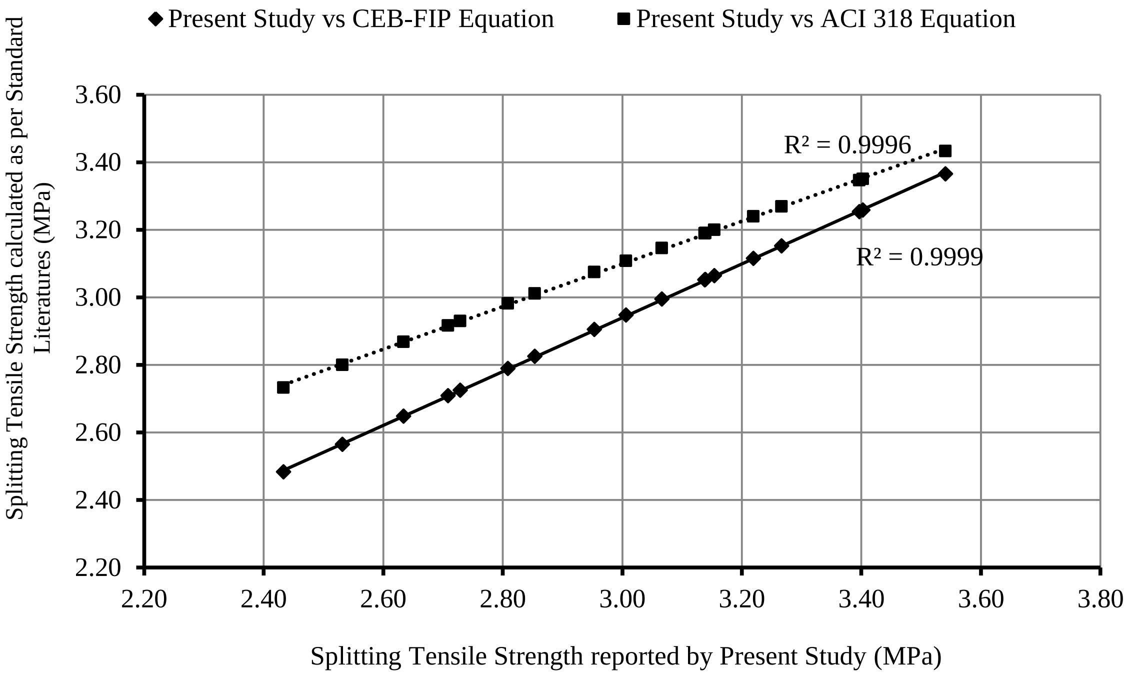

Fig. 4.15 : Relation between Splitting Tensile Strength Results as per Present Study and as per Equations given in Standard Literatures

From Figure 4.15, it can be observed that coefficient of determination, R^2, for splitting tensile strength results as per present study and equation given in ACI 318-14 is 0.9999. Similarly, coefficient of determination, R^2, for splitting tensile strength results as per present study and equation given in CEB-FIP Model Code, 2010 is 0.9999. As coefficient of determination is nearly equal to 1, so we can say that the investigations in the present study have a strong correlation with standard literatures. This also verifies the accuracy of the splitting tensile strength and compressive strength results obtained in the present study.

4.6 Durability Properties of Concrete:

4.6.1 Water Absorption:

Water absorption of different concrete mixes was evaluated at age of 7 days and 28 days, after initial curing of 28 days to study the effect of partial substitution of natural sand with sandstone quarry dust and observations are given in Table 4.17.

TABLE 4.17 : Water Absorption of Concrete Mixes at Different Ages

Mix Designation	Water Absorption (%)			
	7 Days after Initial Curing of 28 Days		28 Days after Initial Curing of 28 Days	
	Individual	Average	Individual	Average
CM	3.01	3.01	2.54	2.64
	2.93		2.72	
	3.10		2.66	
QD10	2.68	2.74	2.27	2.36
	2.62		2.37	
	2.90		2.44	
QD20	2.34	2.24	1.96	1.77
	2.12		1.68	
	2.27		1.67	
QD30	1.84	1.91	1.31	1.41
	1.96		1.54	
	1.93		1.38	
QD40	1.60	1.73	1.02	1.12
	1.77		1.12	
	1.82		1.21	
QD50	1.58	1.44	0.82	0.89
	1.41		0.99	
	1.34		0.85	

From Table 4.17, it can be observed that partial substitution of natural sand with sandstone quarry dust has very significant effect on water absorption of concrete at all ages. Water absorption of all concrete mixtures at 28 days after initial curing of 28 days is less than the respective water absorption of concrete mixtures at 7 days after initial curing of 28 days. Moreover, at all ages, water absorption of concrete mixtures goes on decreasing with increase in sand replacement level. At 7 days after initial curing of 28 days, water absorption of control concrete was 3.01%, whereas water absorption of concrete mixes with 10%, 20%, 30%, 40% and 50% sand replacement was 2.74%, 2.24%, 1.91%, 1.73% and 1.44%, respectively. 28 days after initial curing of 28 days, water absorption of control concrete was 2.64%, whereas water absorption of concrete mixes with 10%, 20%, 30%, 40% and 50% sand replacement was 2.36%, 1.77%, 1.41%, 1.12% and 0.89%, respectively. Cordeiro et. al. (2016) also reported decrease in water absorption of concrete with increase in sand replacement with granite dust.

Graphical representation of the water absorption results of concrete mixtures at different ages if given in Fig. 4.16.

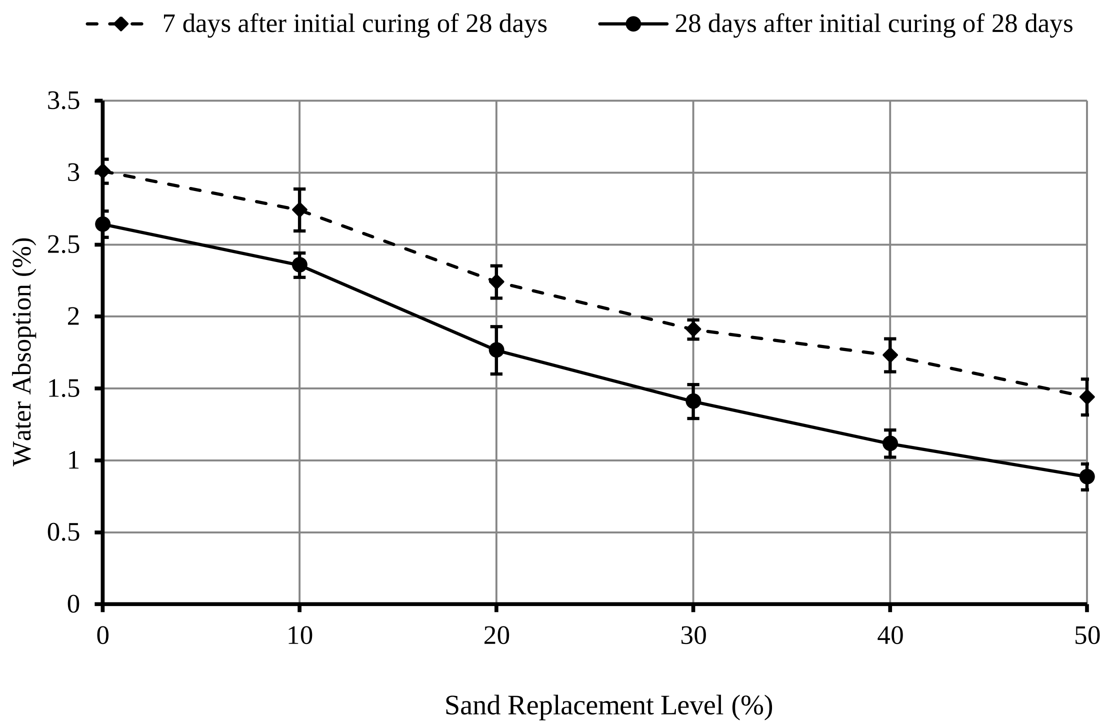

Fig. 4.16 : Effect of Replacement of Natural Sand with Sandstone Quarry Dust on Water Absorption of Concrete

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The decrease in water absorption of concrete with ages can be explained on the fact that hydration of cement and formation of hydration products continues with age as long as sufficient curing is done. Thus, compressive strength of concrete goes on increasing with age and hence, water absorption of concrete goes on decreasing with age. The other fact is that with the substitution of natural sand with sandstone quarry dust, density of concrete goes on increasing with increase in sand substitution rate. Micro-fines present in quarry dust tend to fill up the voids present in concrete and making the concrete microstructure denser, leaving lesser voids, as compared to control concrete to absorb water. This reduction in voids continues with increase in natural sand replacement level. Thus, at both ages, water absorption of concrete decreases with increase in sand substitution rate.

Regression analysis has been done to find the correlation between 1-day density of concrete mixes and their respective water absorption at different ages, which is demonstrated in Fig. 4.17.

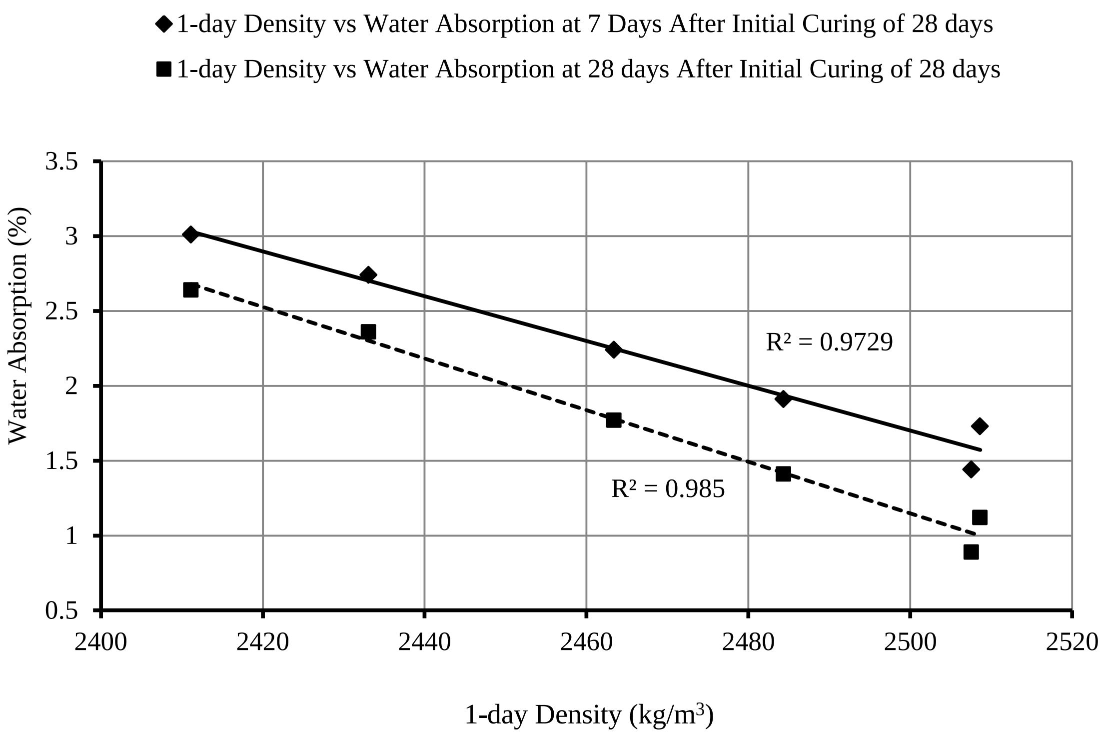


Fig. 4.17 : Relation between 1-day Density and Water Absorption of Concrete Mixes

From Fig. 4.18, it can be observed that with increase in 1-day density, water absorption of concrete mixtures is decreasing at all ages of testing. Coefficient of determination, R^2, for linear relation between 1-day density and respective water absorption at 7 days and 28 days after initial curing of 28 days comes out to be 0.9729 and 0.985, respectively, which is close to unity. This demonstrates a strong correlation between regression curve and data points.

4.6.2 Sorptivity:

Sorptivity of different concrete mixes was evaluated at age of 7 days and 28 days, after initial curing of 28 days to study the effect of partial substitution of natural sand with sandstone quarry dust and observations are given in Table 4.18.

TABLE 4.18
Sorptivity of Concrete Mixes at Different Ages

Mix Designation	Sorptivity ($mm^3/mm^2/min^{0.5}$)			
	7 Days after Initial Curing of 28 Days		28 Days after Initial Curing of 28 Days	
	Individual	Average	Individual	Average
CM	0.1763	0.1777	0.1646	0.1638
	0.1791		0.1649	
QD10	0.1469	0.1441	0.1275	0.1288
	0.1413		0.1300	
QD20	0.1022	0.1037	0.0922	0.0908
	0.1051		0.0893	
QD30	0.0849	0.0840	0.0699	0.0712
	0.0831		0.0724	
QD40	0.0707	0.0721	0.0577	0.0583
	0.0735		0.0588	
QD50	0.0625	0.0619	0.0496	0.0491
	0.0612		0.0486	

From Table 4.18, it can be observed that replacement of natural sand with sandstone quarry dust has very significant effect on sorptivity of concrete at all ages. Sorptivity of all concrete mixtures at 28 days after initial curing of 28 days is less than the respective sorptivity of concrete mixtures at 7 days after initial curing of 28 days. Moreover, at all ages, sorptivity of concrete mixtures goes on decreasing with increase in sand replacement level. At 7 days after initial curing of 28 days, sorptivity of control concrete (in $mm^3/mm^2/min^{0.5}$) was 0.1777, whereas sorptivity of concrete mixes (in $mm^3/mm^2/min^{0.5}$) with 10%, 20%, 30%, 40% and 50% sand replacement was 0.1441, 0.1037, 0.0840, 0.0721 and 0.0619, respectively. At 28 days after initial curing of 28 days, sorptivity of control concrete (in $mm^3/mm^2/min^{0.5}$) was 0.1638, whereas sorptivity of concrete mixes (in $mm^3/mm^2/min^{0.5}$) with 10%, 20%, 30%, 40% and 50% sand replacement was 0.1288, 0.0908, 0.0712, 0.0583 and 0.0491, respectively. This observation is exactly same as that of in case of water absorption.

Graphical representation of the sorptivity results of concrete mixtures at different ages if given in Fig. 4.18.

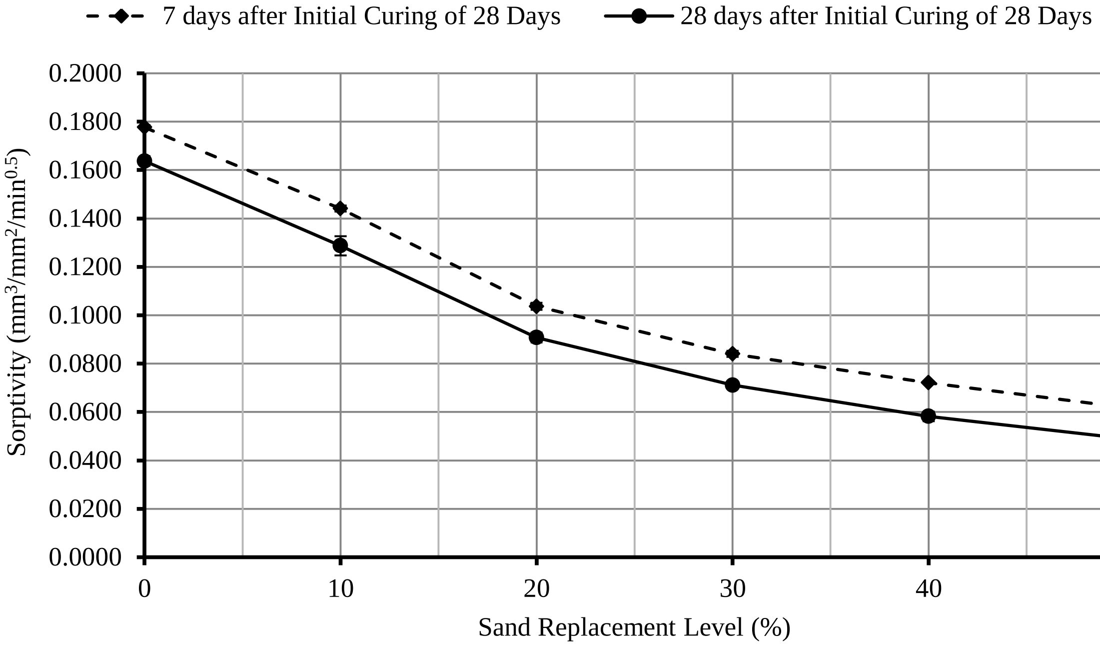


Fig. 4.18 : Effect of Replacement of Natural Sand with Sandstone Quarry Dust on Sorptivity of Concrete

The decrease in sorptivity of concrete with ages can be explained on the fact that hydration of cement and formation of hydration products continues with age as long as sufficient curing is done. Thus, compressive strength of concrete goes on increasing with age and hence, sorptivity of concrete goes on decreasing with age. The other fact is that with the partial substitution of natural sand with sandstone quarry dust, density of concrete goes on increasing with increase in sand substitution rate. Micro-fines present in sandstone quarry dust tend to fill up the voids present in concrete and making the concrete microstructure denser, leaving lesser voids, as compared to control concrete. Micro-fines are not only reducing size of the voids, but also modifying the internal pore structure by blocking interconnecting capillary pores. That is the reason of decrease in sorptivity of concrete with inclusion of sandstone quarry dust as partial substitute of natural sand.

Regression analysis has been done to find the correlation between 1-day density of concrete mixes and their respective sorptivity at different ages, which is demonstrated in Fig. 4.19.

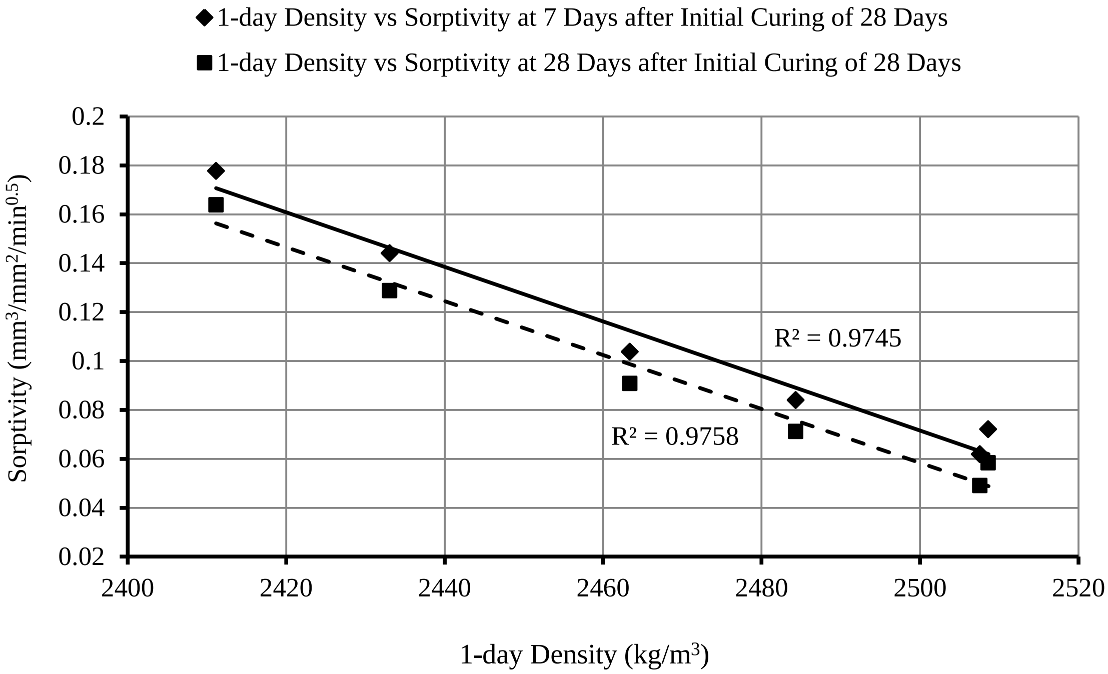


Fig. 4.19 : Relation between 1-day Density and Sorptivity of Concrete Mixes

From Figure 4.19, it can be observed that with increase in 1-day density, sorptivity of concrete mixtures decreases at all ages. Coefficient of determination, R^2, for linear relation between 1-day density and respective sorptivity at 7 days and 28 days after initial curing of 28 days comes out to be 0.9745 and 0.9758, respectively, which is close to unity. This demonstrates a strong correlation between regression curve and data points.

4.6.3 Rapid Chloride-ion Permeability:

Rapid chloride-ion permeability test was conducted and charge passed in coulombs was recorded for different concrete mixes at age of 28 days to study the effect of partial substitution of natural sand with sandstone quarry dust and observations are given in Table 4.19.

TABLE 4.19 : Rapid Chloride-ion Permeability Test Results

Mix Notation	Total Charge Passed at 28 days (Coulombs)	Average Charge Passed (Coulombs)	Chloride-Ion Permeability as per ASTM C-1202
CM	1992	2173	Moderate
	2353		
QD10	2074	1995	Low
	1916		
QD20	1893	1834	Low
	1774		
QD30	1614	1697	Low
	1779		
QD40	1743	1684	Low
	1625		
QD50	1779	1888	Low
	1996		

Graphical representation of rapid chloride-ion permeability test results for different concrete mixes is given in Fig. 4.20.

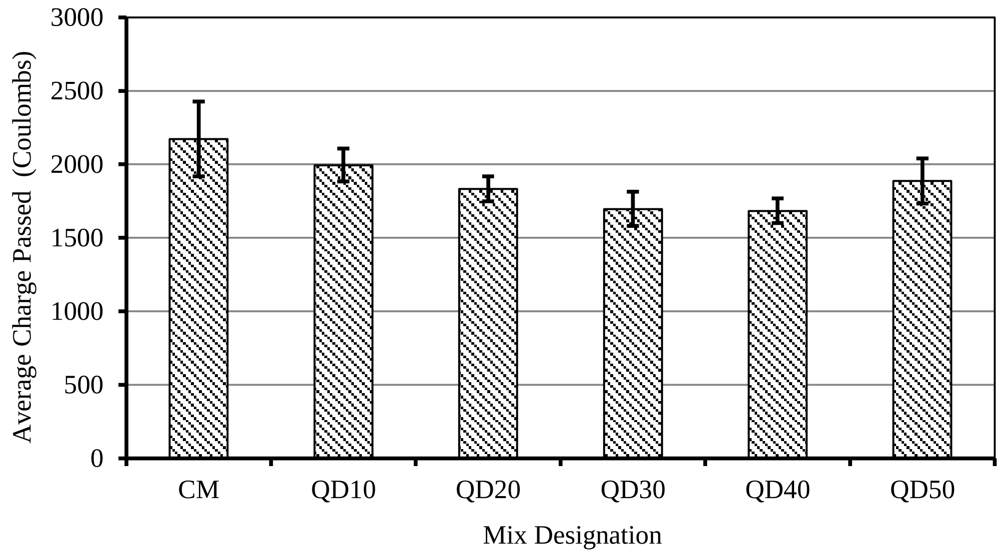


Fig. 4.20 : Rapid Chloride-ion Permeability Test Results for Concrete Mixes at 28 Days

The increase in chloride-ion penetration resistance can be attributed to increase in density as well as compressive strength of concrete with increase in partial substitution of natural sand with sandstone quarry dust. As explained earlier, with increase in sand substitution rate, micro-fines present in sandstone quarry dust tend to fill up the voids in concrete, giving a denser matrix as compared to control concrete, leaving less voids. That may be the reason behind the increase in chloride-ion penetration resistance. It should be noted that concrete mix with 40% sand replacement level has the lowest chloride-ion permeability, which is the same concrete mix that has maximum compressive strength at 28 days. Figure 4.21 demonstrates the correlation between total charge passed at 28 days and average compressive strength of the respective concrete mix at 28 days.

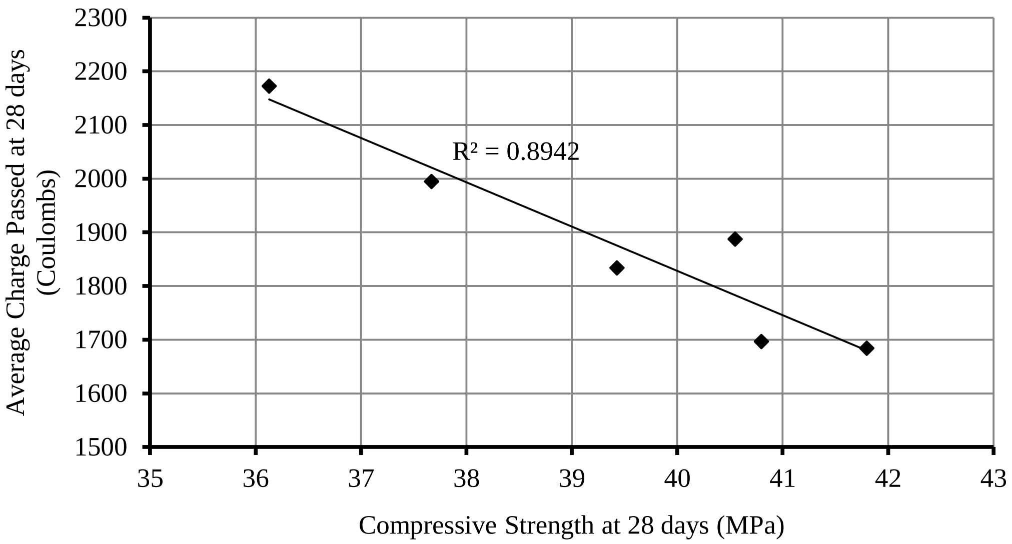


Fig. 4.21 : Relation between Average Charge Passed at 28 Days and Average Compressive Strength at 28 Days

From Fig. 4.21, it can be observed that the coefficient of determination, R^2, comes out to be 0.8942, which is close to unity. It means there is a strong correlation between regression curve and data points.

The decrease in chloride-ion penetration resistance at 50% sand replacement level may be due to decrease in workability of concrete. It has been observed that there is a gradual decrease in workability of concrete with increase in sand replacement level and this decrease is more profound in concrete mixes with higher sand replacement level. As concrete mix with 50% sand replacement has lowest workability among all concrete mixtures, which may have resulted into improper compaction leading to comparatively poor microstructure as compared to other concrete mixtures. It should also be noted that even if average total charge passed had increase for concrete mix with 50% sand replacement, but still, it is well below than that of control concrete.

4.7 Mineralogical Characteristics and Microstructural Analysis:

4.7.1 X-ray Diffraction Analysis

X-ray diffraction analysis was performed to identify various cement phases in concrete and also to identify any qualitative changes occurred in cement phases due to the partial substitution of natural sand with sandstone quarry dust so as to find out the influence of addition of sandstone quarry dust as a partial substitute of natural sand on hydration process of cement. X-ray diffraction analysis was performed on all concrete mixes at age of 28 days and 90 days. X-ray diffraction pattern was recorded with X-ray diffractometer at diffraction angle 2θ ranged between 10° to 80° with CuKα radiation (λ=1.54 Å) in steps of 2θ=0.013°. X-ray diffractogram of control mix at 28 days is given in Fig. 4.22, at diffraction angle 2θ ranged between 10° to 70°.

From Fig. 4.22, it can be observed that at age of 28 days, various phases present in control concrete were quartz, calcium silicate, portlandite, calcium silicate hydrate, calcium aluminium silicate hydrate and calcite.

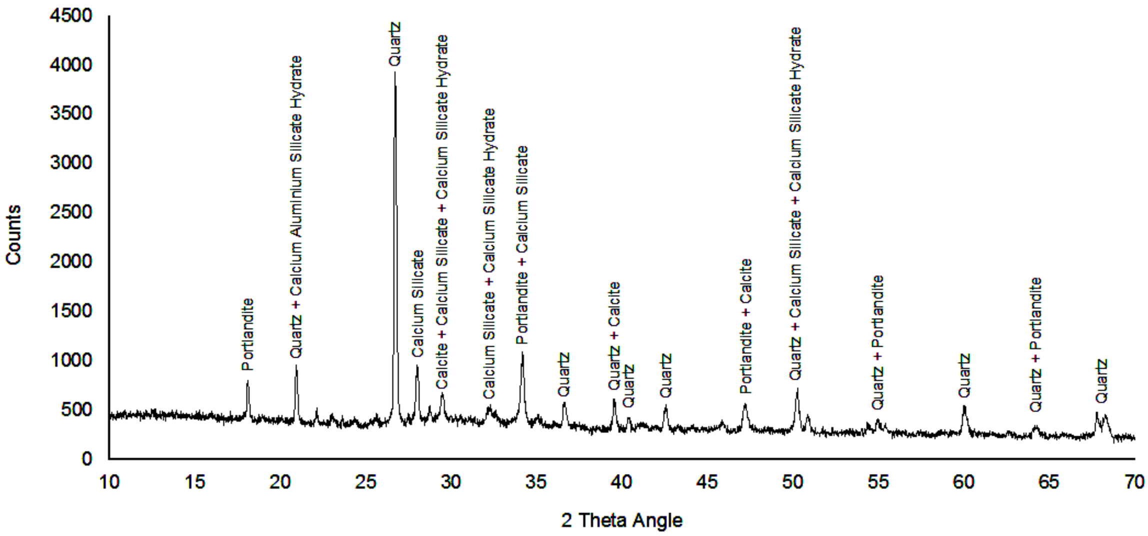


Fig. 4.22 : X-ray Diffractogram of Control Concrete at 28 Days

X-ray diffractograms of concrete mixes with 10%, 20%, 30%, 40% and 50% sandstone quarry dust are given in Figs. 4.23 to 4.27, respectively, at diffraction angle 2θ ranged between 10° to 70°. It can be observed that at age of 28 days, various phases present in control concrete were quartz, portlandite, calcium silicate hydrate, calcium silicate, calcium aluminium silicate hydrate and calcite. Thus it can be said that there is no qualitative change in cement phases with addition of sandstone quarry dust as replacement of natural sand.

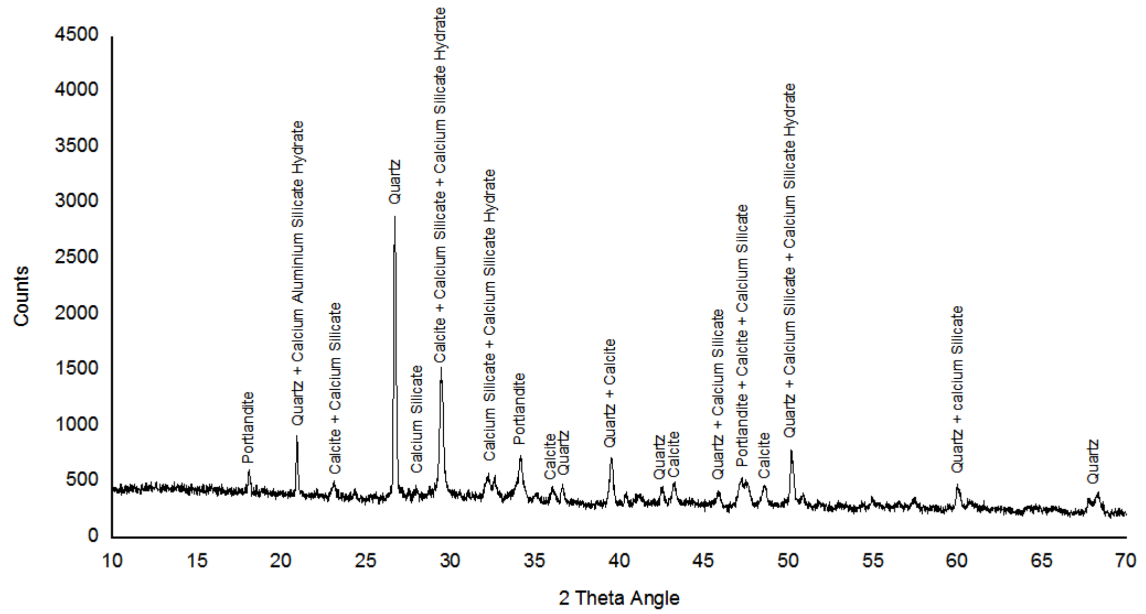


Fig. 4.23 : X-ray Diffractogram of Concrete Mix Containing 10% Sandstone Quarry Dust at 28 Days

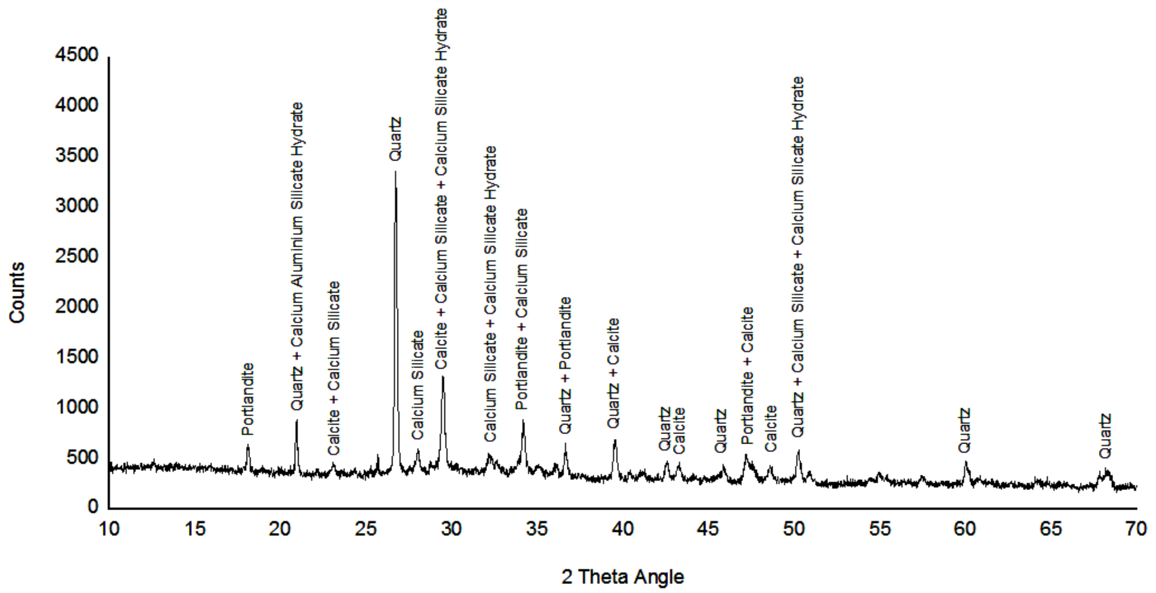


Fig. 4.24 : X-ray Diffractogram of Concrete Mix Containing 20% Sandstone Quarry Dust at 28 Days

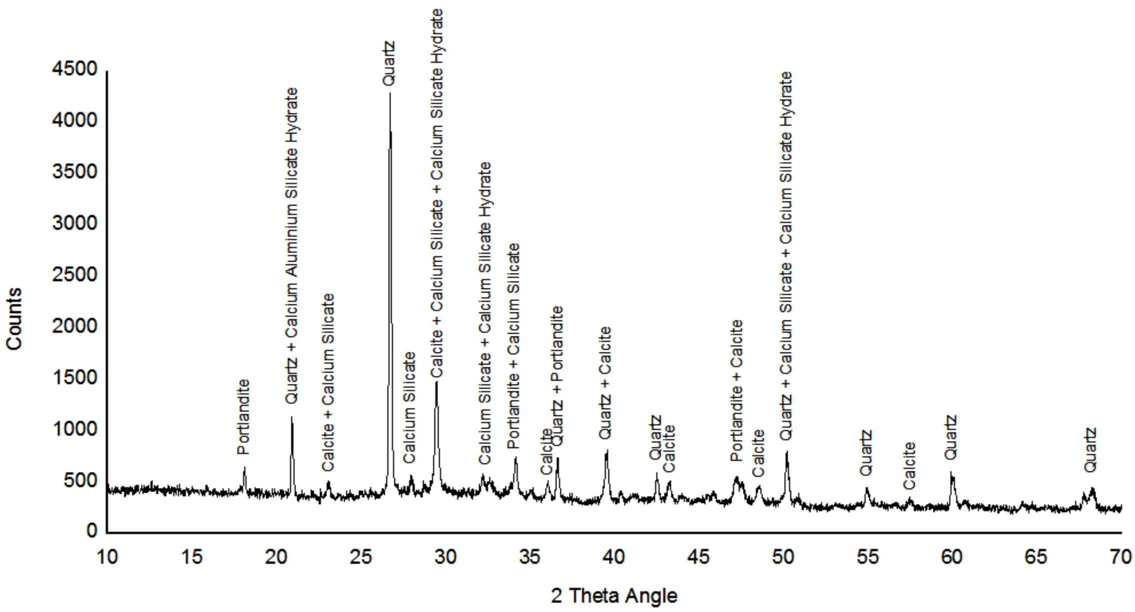


Fig. 4.25 : X-ray Diffractogram of Concrete Mix Containing 30% Sandstone Quarry Dust at 28 Days

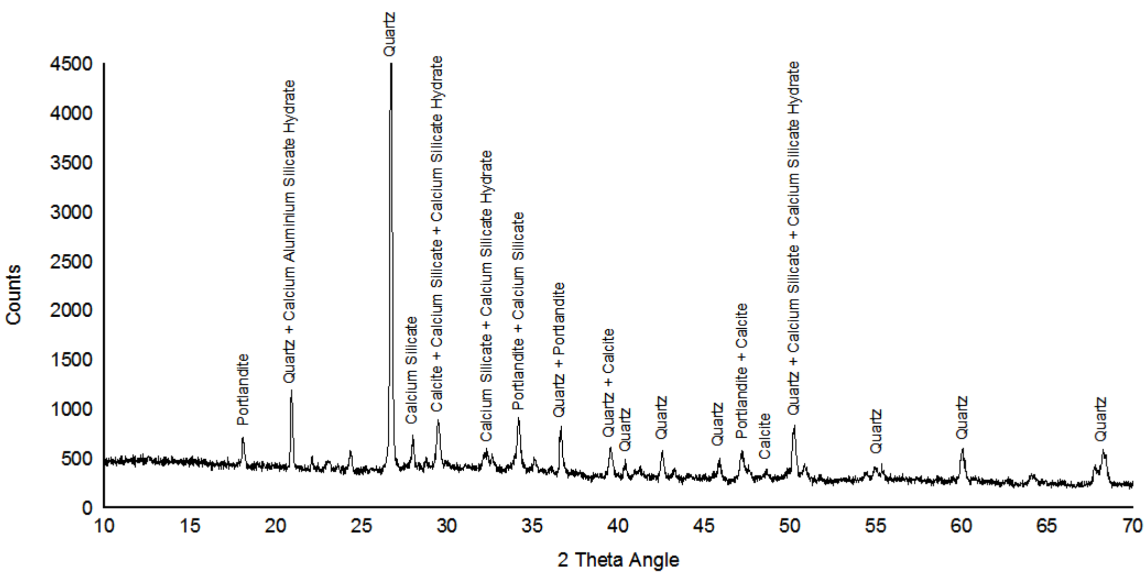


Fig. 4.26 : X-ray Diffractogram of Concrete Mix Containing 40% Sandstone Quarry Dust at 28 Days

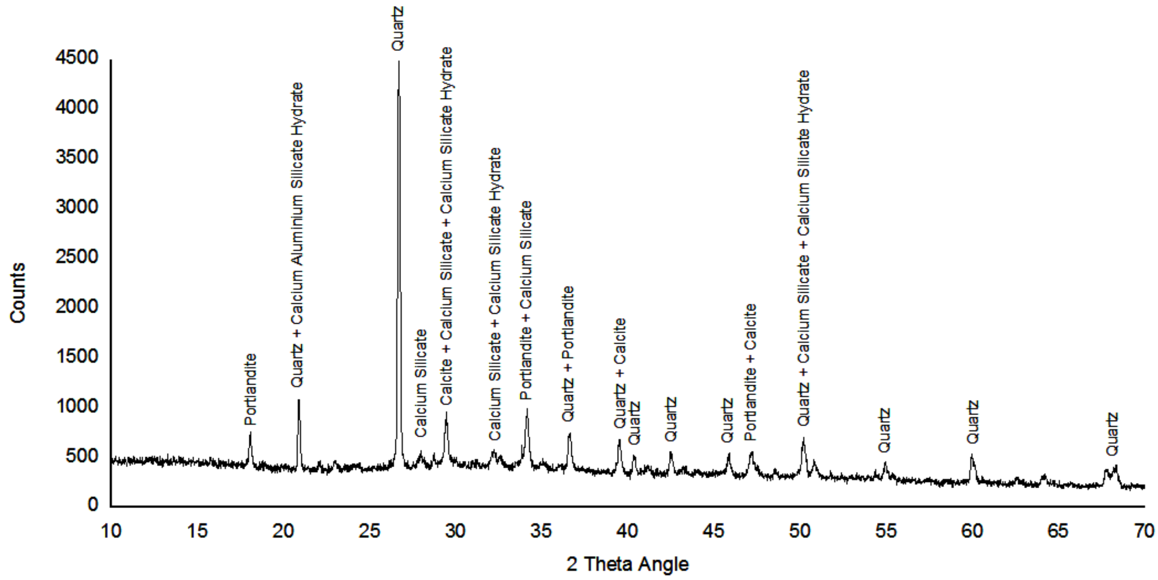


Fig. 4.27 : X-ray Diffractogram of Concrete Mix Containing 50% Sandstone Quarry Dust at 28 Days

To see the changes in cement phases at later ages, X-ray diffraction was also performed at 90 days. Fig. 4.28 shows X-ray diffractogram of control mix at 90 days at diffraction angle 2θ ranged between 10° to 70°.

From Fig. 4.28, it can be observed that at age of 90 days, various phases present in control concrete were quartz, calcium silicate, portlandite, calcium silicate hydrate, calcium aluminium silicate hydrate and calcite.

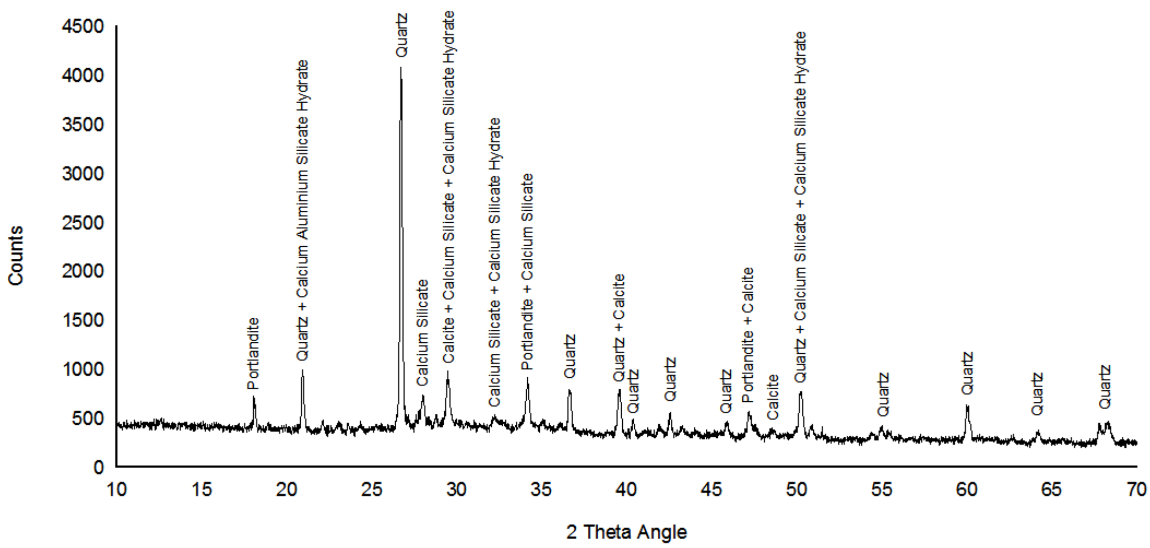


Fig. 4.28 : X-ray Diffractogram of Control Concrete at 90 Days

Similarly, X-ray diffractograms of concrete mixes with 10%, 20%, 30%, 40% and 50% sandstone quarry dust at age of 90 days are given in Figs. 4.29 to 4.33, respectively, at diffraction angle 2θ ranged between 10° to 70°.

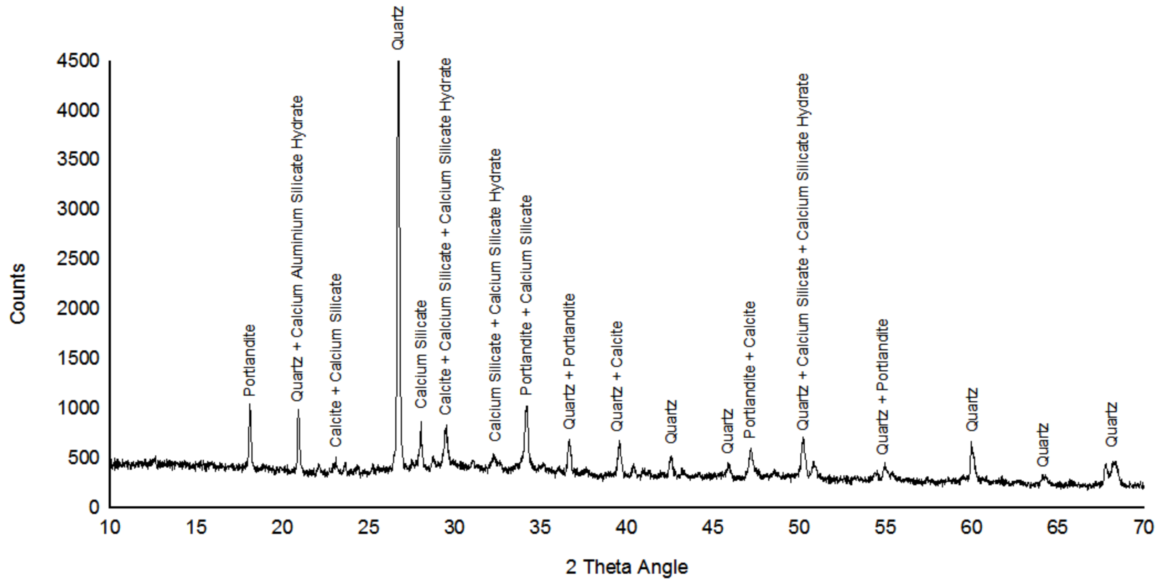


Fig. 4.29 : X-ray Diffractogram of Concrete Mix Containing 10% Sandstone Quarry Dust at 90 Days

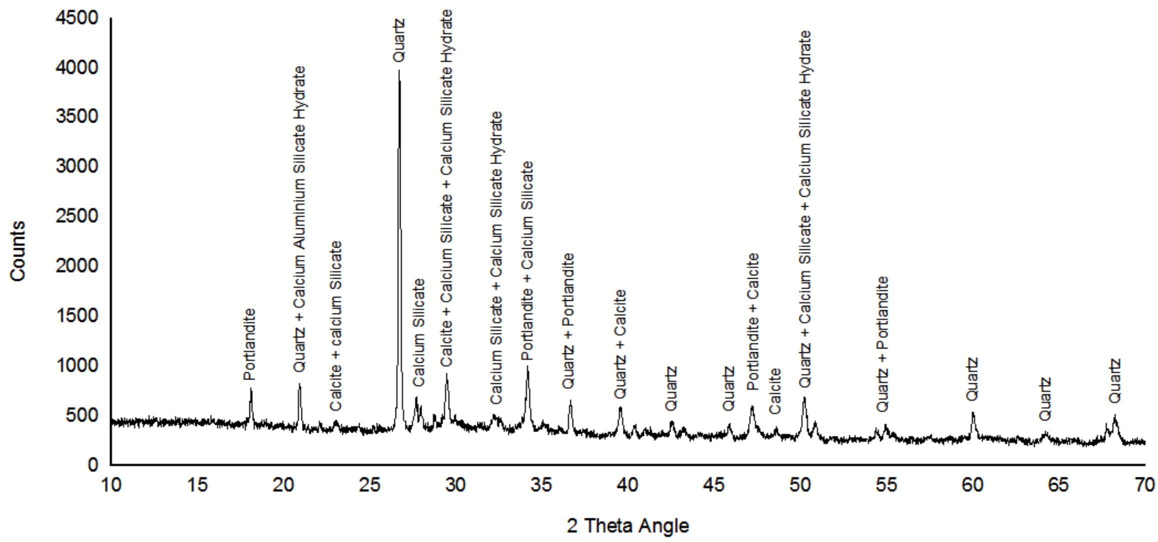


Fig. 4.30 : X-ray Diffractogram of Concrete Mix Containing 20% Sandstone Quarry Dust at 90 Days

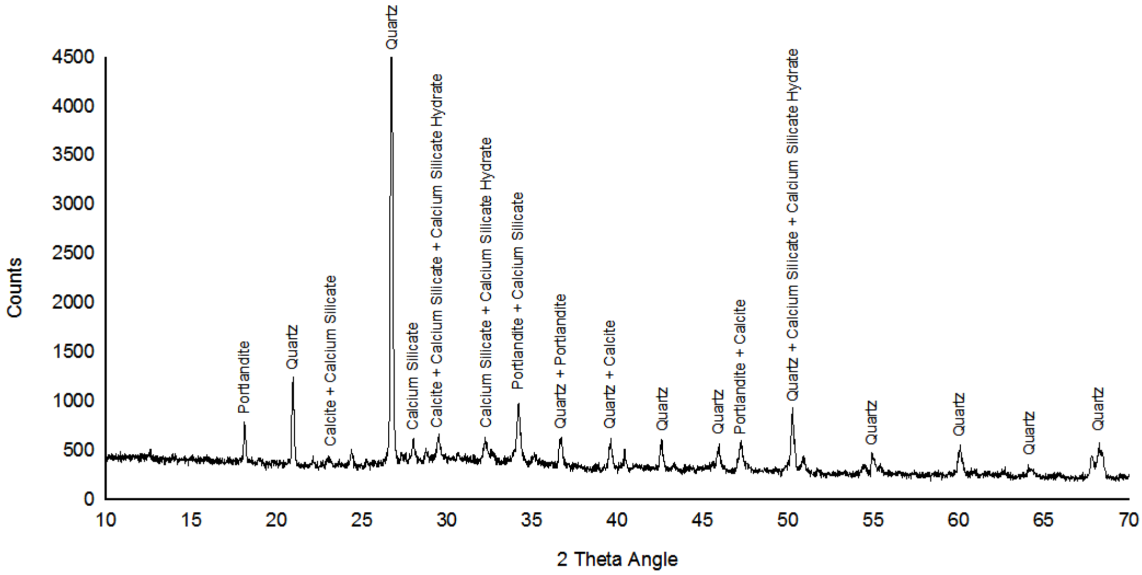


Fig. 4.31 : X-ray Diffractogram of Concrete Mix Containing 30% Sandstone Quarry Dust at 90 Days

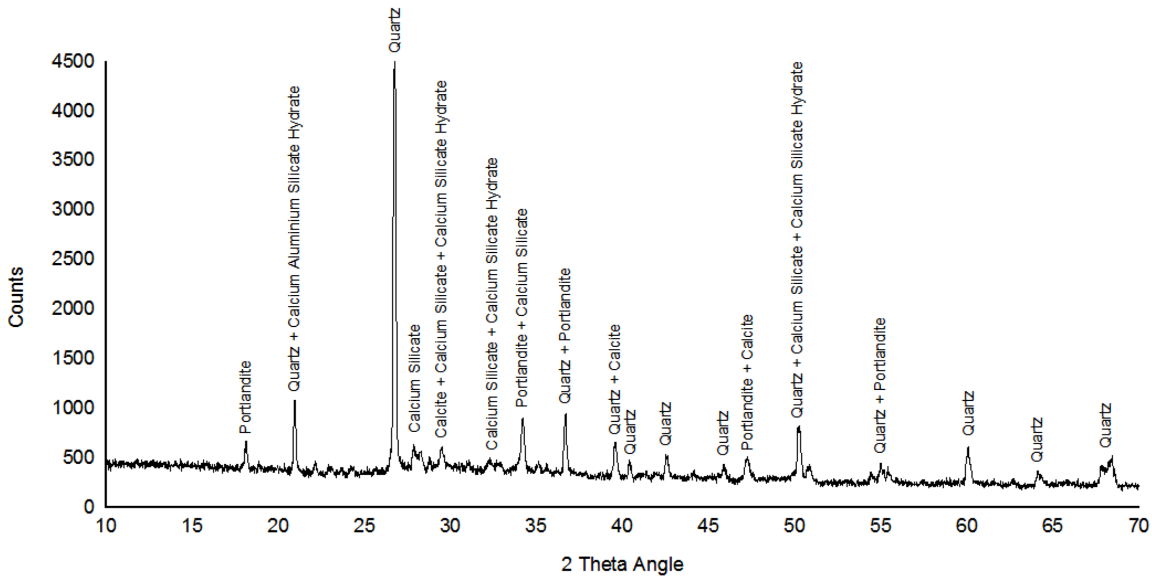


Fig. 4.32 : X-ray Diffractogram of Concrete Mix Containing 40% Sandstone Quarry Dust at 90 Days

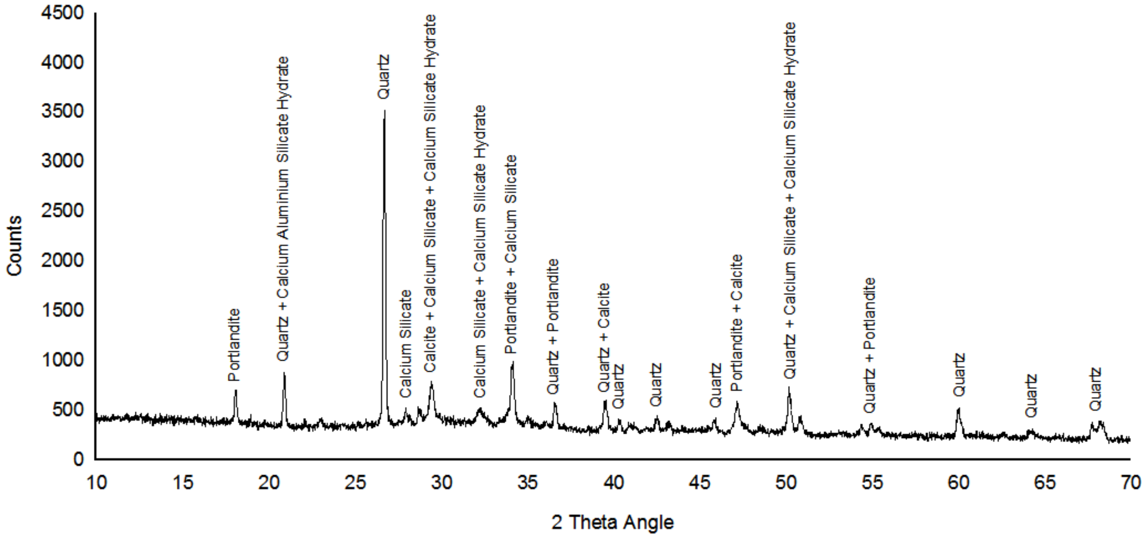


Fig. 4.33 : X-ray Diffractogram of Concrete Mix Containing 50% Sandstone Quarry Dust at 90 Days

Figs. 4.29 to 4.33, it can be observed that at age of 90 days, various phases present in concrete mixes containing quarry dust were quartz, calcium silicate, portlandite, calcium silicate hydrate, calcium aluminium silicate hydrate and calcite. Comparing the X-ray diffraction pattern of control concrete and all the concrete mixes containing sandstone quarry dust, it can be said that no new hydration products have formed in concrete mixes containing sandstone quarry dust as a partial substitute of natural sand. Thus, there is no qualitative change in various phases with the addition of sandstone quarry dust as a partial substitution of natural sand in concrete.

Comparing the X-ray diffraction patterns of corresponding quarry dust concrete mixtures at 28 days and 90 days, we can say that no new hydration products have formed at later ages. Thus, there is no qualitative change in various phases with age by the addition of sandstone quarry dust as a partial substitution of natural sand in concrete.

So it can be concluded that sandstone quarry dust is an inert material, which has no direct involvement in the hydration process of the cement. As discussed earlier, inclusion of sandstone quarry dust as a partial substitution of natural sand in concrete results more favourable conditions for better hydration of cement due to its higher specific surface area. However, quarry dust itself does not take part in the hydration process.

4.7.2 Scanning Electron Microscope (SEM) Analysis:

To study the various changes in the microstructure of concrete with addition of sandstone quarry dust as a partial substitute of natural sand, scanning electron microscope (SEM) analysis was performed. Concrete samples collected from all concrete mixes at age of 28 days and 90 days were analysed at different magnifications to study the microstructure of each concrete mix.

Figure 4.34 and 4.35 show the SEM morphology of different concrete mixes at age 28 days at magnification factor of 1000 and 5000, respectively.

It can be observed that inclusion of sandstone quarry dust has a very profound effect on microstructure of concrete. Control concrete has maximum voids among all concrete mixes. As the substitution rate of natural sand with sandstone quarry dust is increasing, voids goes on reducing.

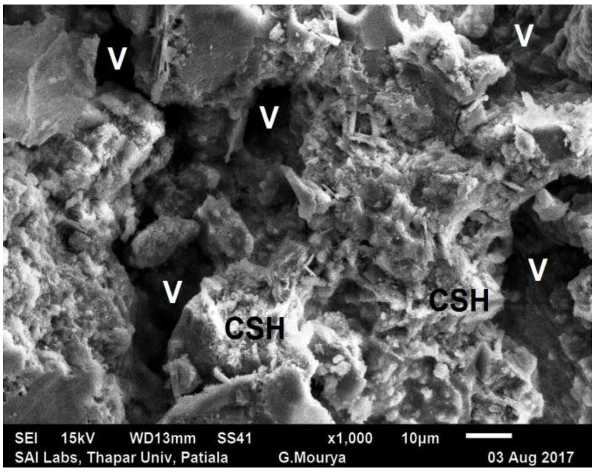
Fig. 4.36 and 4.37 show the SEM morphology of different concrete mixes at age 90 days at magnification factor of 1000 and 5000, respectively. Here also, Control concrete has maximum voids among all concrete mixes and as the substitution rate of natural sand with sandstone quarry dust is increasing, voids goes on reducing. There is no change in microstructure of concrete at 90 days, as compared to 28 days.

The improvement in microstructure of concrete can be attributed to the filling effect of sandstone quarry dust micro-fines, which tends to fill up voids present in concrete, making the microstructure more dense.

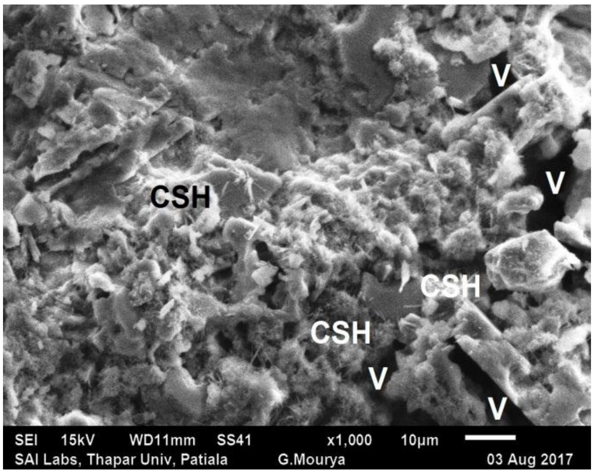
Microstructure of concrete plays a very significant role in affecting hardened as well as durability properties of concrete. The reduction in voids in concrete mixtures containing sandstone quarry dust was the main reason behind its superior hardened and durability properties as compared to control mix.

SEM analysis also confirmed the reason behind the increase in density of concrete with sandstone quarry dust as partial replacement of natural sand. SEM images show that at 28 days as well as 90 days, concrete mix with 40% sand replacement level has minimum voids and thus, it has maximum density.

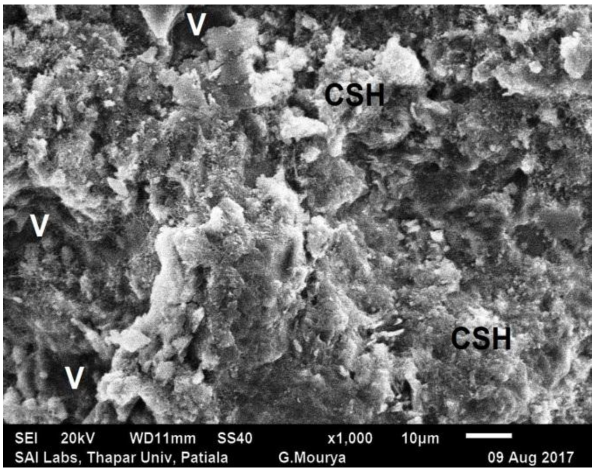
It can be concluded that the improvement in strength and durability properties of concrete with addition of sandstone quarry dust as partial substitute of natural sand can be mainly attributed to the denser microstructure of concrete mixes containing sandstone quarry dust as X-ray diffraction analysis shows that sandstone quarry dust in an inert material and does not take part in hydration of cement.



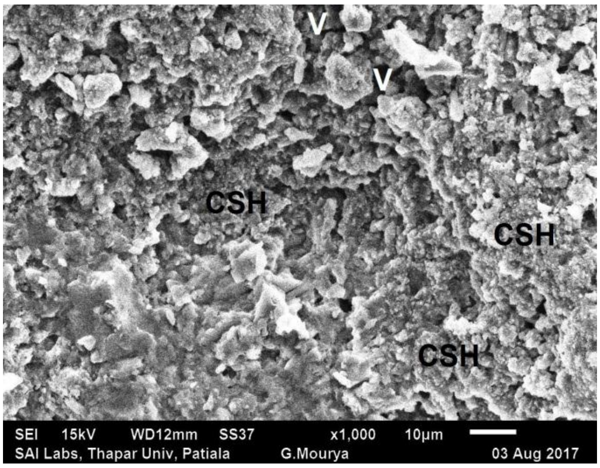
CM : Control Mix



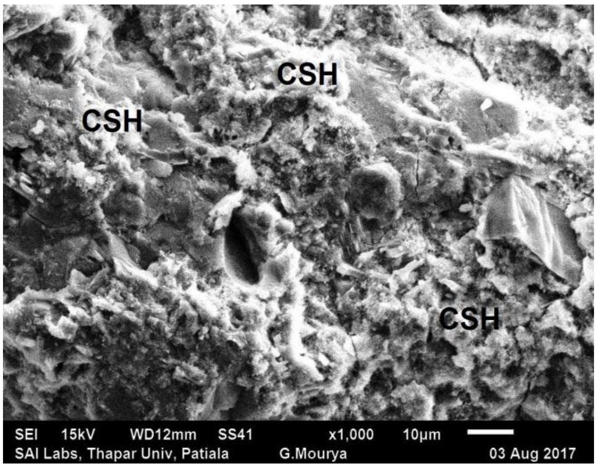
QD10 : 10% Sand Replacement



QD20 : 20% Sand Replacement

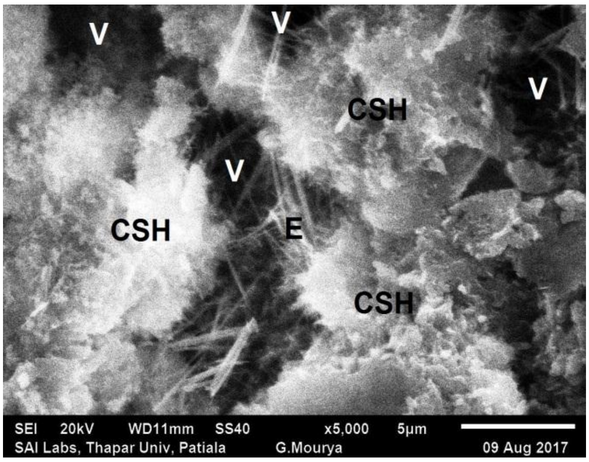


QD30 : 30% Sand Replacement

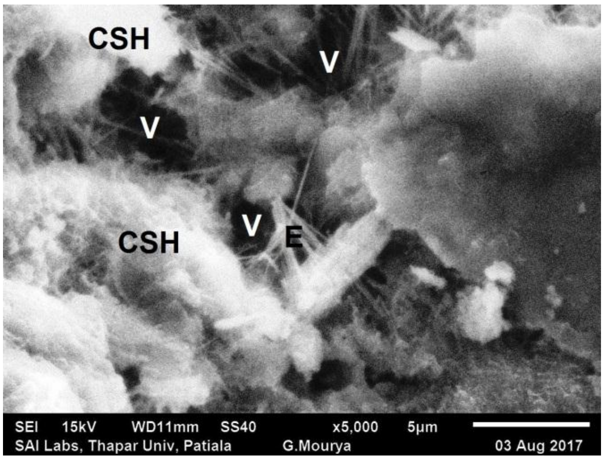


QD40 : 40% Sand Replacement

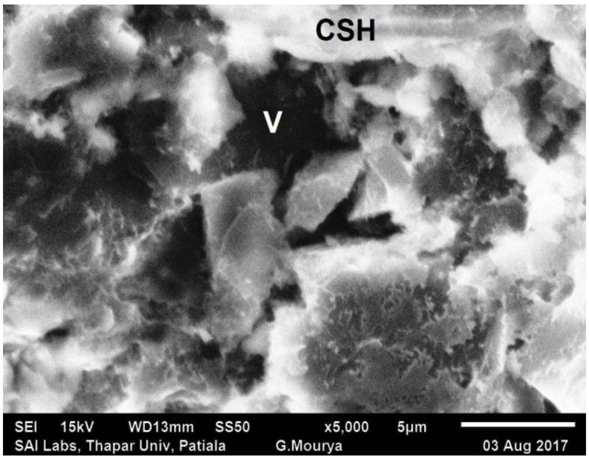
Fig. 4.34 : SEM Morphology of Concrete Containing Sandstone Quarry Dust as Partial Replacement of Natural Sand at Age of 28 Days with Magnification Factor of 1000



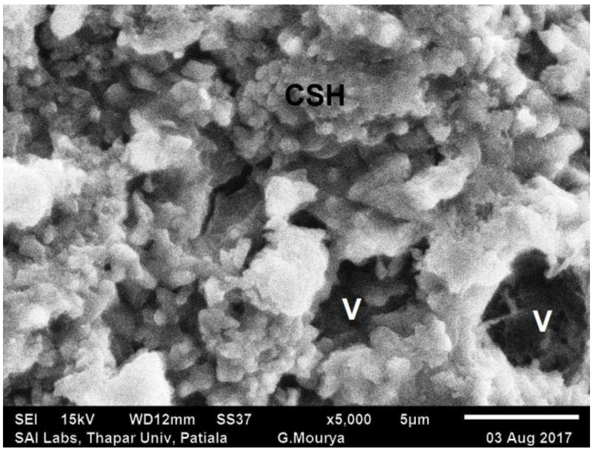
CM : Control Mix



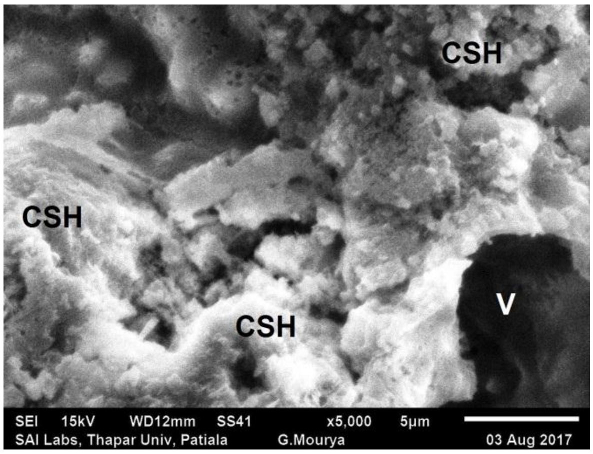
QD10 : 10% Sand Replacement



QD20 : 20% Sand Replacement

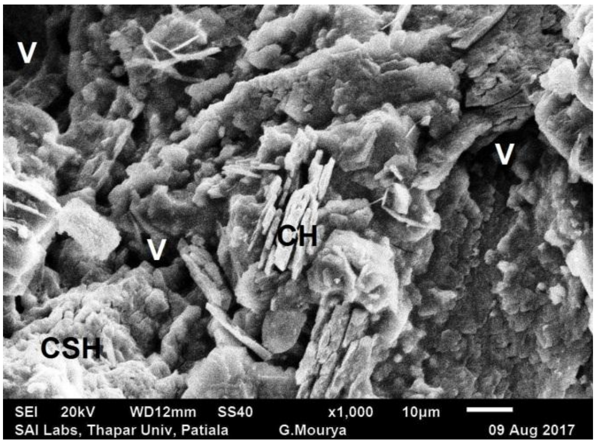


QD30 : 30% Sand Replacement

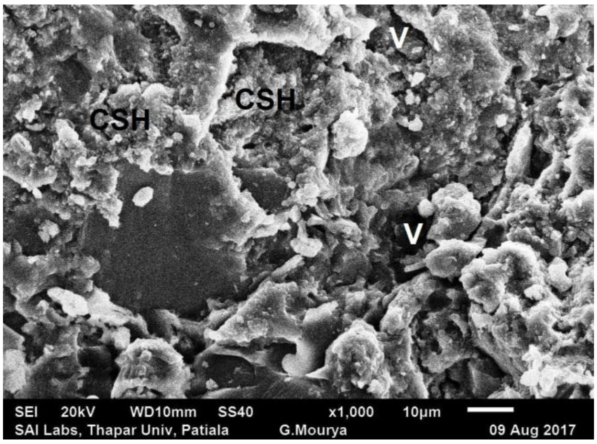


QD40 : 40% Sand Replacement

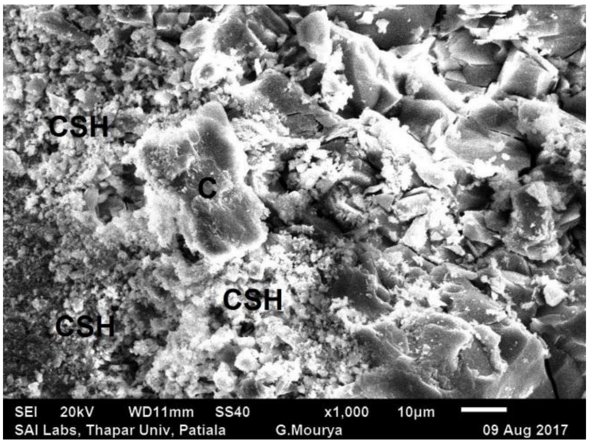
Fig. 4.35 : SEM Morphology of Concrete Mixes Containing Sandstone Quarry Dust as Partial Replacement of Natural Sand at Age of 28 Days with Magnification Factor of 5000



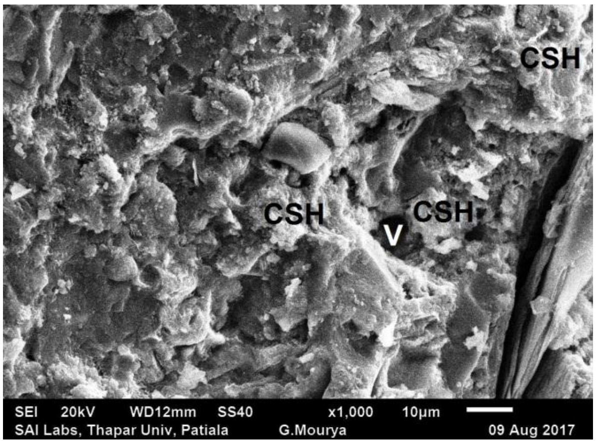
CM : Control Mix



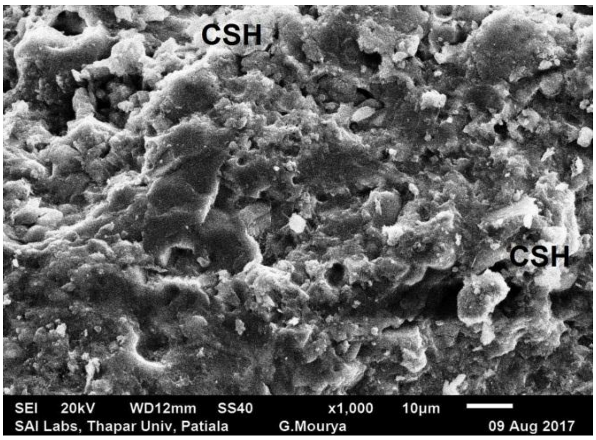
QD10 : 10% Sand Replacement



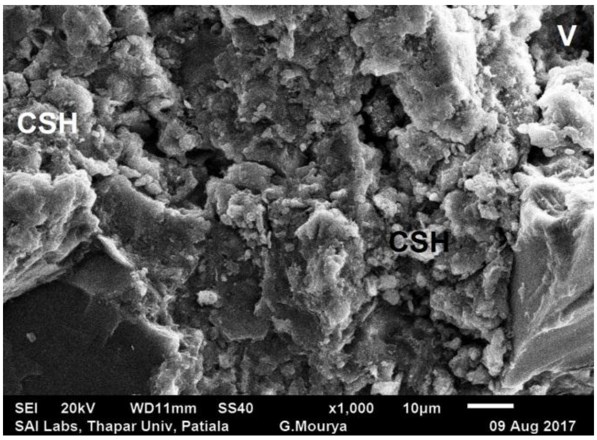
QD20 : 20% Sand Replacement



QD30 : 30% Sand Replacement

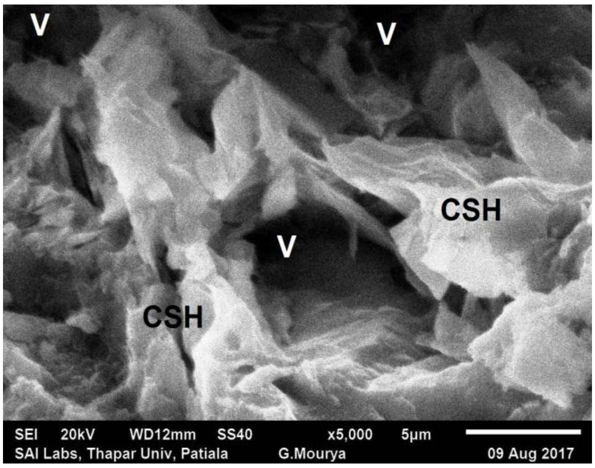


QD40 : 40% Sand Replacement

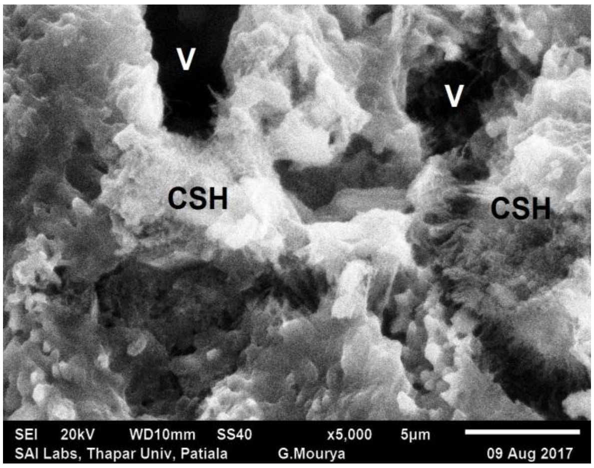


QD50 : 50% Sand Replacement

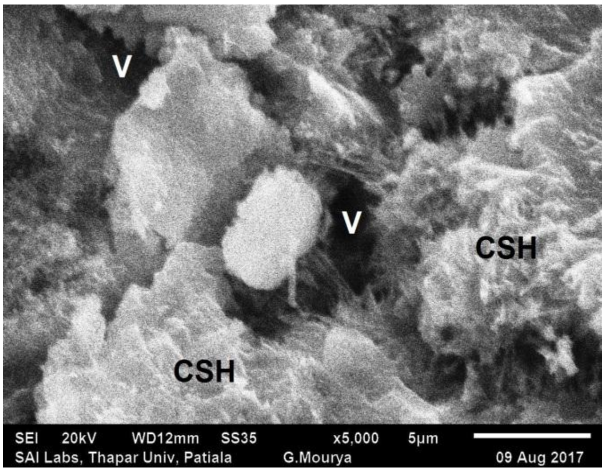
Fig. 4.36 : SEM Morphology of Concrete Mixes Containing Sandstone Quarry Dust as Partial Replacement of Natural Sand at Age of 90 Days with Magnification Factor of 1000



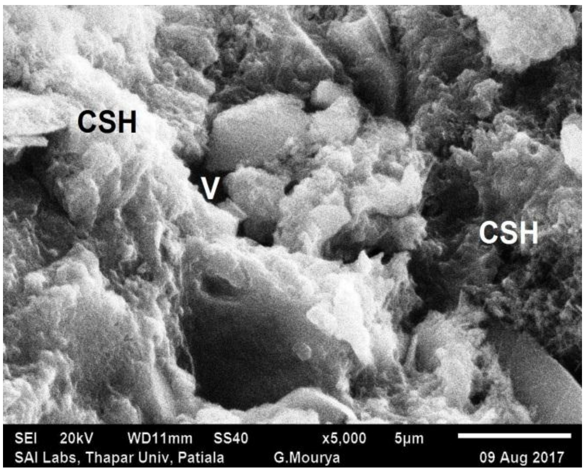
CM : Control Mix



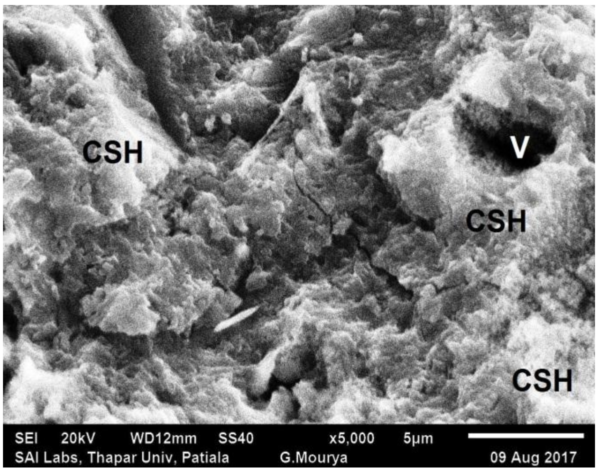
QD10 : 10% Sand Replacement



QD20 : 20% Sand Replacement



QD30 : 30% Sand Replacement



QD40 : 40% Sand Replacement

Fig. 4.37 : SEM Morphology of Concrete Mixes Containing Sandstone Quarry Dust as Partial Replacement of Natural Sand at Age of 28 Days with Magnification Factor of 5000

CHAPTER 5
CONCLUSIONS

5.1 General

The present experimental investigation was conducted to study the suitability of sandstone quarry dust as a partial replacement of natural sand in concrete. Workability, compressive strength, splitting tensile strength, water absorption, sorptivity and rapid chloride-ion permeability of concrete were tested by replacing natural sand with quarry dust at different varying percentages in concrete. XRD and SEM analysis was also done on all concrete mixes to study changes in cement phases as well as microstructure of concrete with the inclusion of sandstone quarry dust as partial replacement of natural sand. Test results indicate that sandstone quarry dust, an industrial by-product, is a suitable substitute of natural sand in concrete.

5.2 Conclusions:

1) Workability of concrete was decreased as the percentage replacement of natural sand with sandstone quarry dust was increased. The increase in specific surface area of fine aggregate due to the micro-fines present in quarry dust and the angular shape of quarry dust particles increased the water demand of concrete and consequently resulted in decrease in workability. However, workability of all concrete mixes up to 50% sand replacement was suitable in structural uses.
2) Density of concrete was increased with increase in replacement of natural sand with sandstone quarry dust. Density of concrete mix with 40% sand replacement level was maximum, which recorded a 4% increase in density as compared to control mix. Filling effect of quarry dust micro-fines to produce a dense microstructure and the higher specific gravity of quarry dust as compared to natural sand was the reason behind the increase in density of concrete.
3) Compressive strength of concrete was increased with inclusion of sandstone quarry dust as partial replacement of natural sand. Concrete mix with 40% sand replacement level had maximum compressive strength at all ages. The increase in compressive strength of concrete was mainly attributed to increase in density of concrete with the inclusion of quarry dust and better conditions for hydration of cement in the presence of quarry dust micro-fines.

4) Splitting tensile strength of concrete was increased with inclusion of sandstone quarry dust as partial replacement of natural sand. Concrete mix with 40% sand replacement level had maximum splitting tensile strength at all ages. The increase in splitting tensile strength of concrete was mainly attributed to increase in density of concrete with the inclusion of quarry dust and better conditions for hydration of cement in the presence of quarry dust micro-fines, same as in case of compressive strength.
5) Water absorption of concrete was decreased with increase in replacement of natural sand with sandstone quarry dust at all ages. Concrete mix with 50% sand replacement level had lowest water absorption among all mixes. The filling effect of quarry dust micro-fines reduced voids, which consequently decreased water absorption of concrete.
6) Sorptivity of concrete was decreased with increase in replacement of natural sand with sandstone quarry dust at all ages. Concrete mix with 50% sand replacement level had lowest sorptivity among all mixes. The reason behind the decrease in sorptivity was that the filling effect of quarry dust micro-fines not only reduced the size of the voids, but also modified the internal pore structure of concrete by blocking interconnecting capillary pores.
7) Chloride-ion penetration resistance was increased with inclusion of sandstone quarry dust as partial replacement of natural sand. Concrete mix with 40% sand replacement level had minimum charge passed among all concrete mixes. The increase in chloride-ion penetration resistance can be mainly attributed to increase in density of concrete with replacement of natural sand with sandstone quarry dust.
8) X-ray diffraction analysis showed that there is no qualitative change in various phases of cement in concrete mixes containing sandstone quarry dust as partial replacement of natural sand as compared to control concrete. Various phases present in all concrete mixes were identified as quartz, portlandite, calcium silicate hydrate, calcium silicate, calcium aluminium silicate hydrate and calcite. Thus, quarry dust can be considered as an inert material.
9) SEM analysis of concrete mixes clearly demonstrated the filling effect of sandstone quarry dust micro-fines in concrete. Control mix had maximum voids at all ages, which decreased continuously as the replacement of natural sand with quarry dust was increased. Concrete mixes with 40% and 50% sand replacement seemed to have minimum voids and most dense microstructure among all mixes.

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