https://doi.org/10.48048/tis.2022.4946

Use of Modified Andreassen Curve in Optimizing Mixes

Rutvik Mane[1,*], Nitin Chaphalkar[1] and Smita Patil[2]

[1]Department of Civil, Government College of Engineering, Karad, India
[2]National Institute of Construction Management and Research, School of Construction Management, Pune, India

([*]Corresponding author's e-mail: rutvikmane@gmail.com)

Received: 18 November 2020, Revised: 23 May 2021, Accepted: 30 May 2021

Abstract

Particle packing optimization is a philosophy that has evolved over the years. Its use in concrete proportioning has helped in creating denser and stronger mixes. Numerous packing theories and models have evolved over the course of time to optimize the concrete. Out of which the Modified Andreassen curve has found its practical application in optimizing high-performance concrete. The main objective of the study was to study different particle packing theories and their effects on the mortar mixes and to design the most optimized material which gives the maximum strength. In this paper, the use of quartz sand and Modified Andreassen packing theory has been adopted for the concrete proportioning. This paper also deals with the changes in density and compressive strength in concrete after the application of the Modified Andreassen curve. The EMMA software whose algorithm is based on the Modified Andreassen curve is used for proportioning the concrete. In addition, the effects of admixture dosage on strength have been discussed in the paper. An attempt has been made to create an Ultra-High-Performance Concrete (UHPC) by applying Modified Andreassen Curve and using quartz aggregates. For this a thorough literature review was done, a precast site where the high strength concrete was required was identified and the various tests were conducted on the site itself. The results obtained from this study are quite interesting as 16 % cement was replaced by metakaoline and silica fume and phenomenol strength of 96.18 MPa.

Keywords: Modified Andreassen curve, Ultra-High-Performance Concrete (UHPC), Particle packing optimization, Packing theories and models

Introduction

The optimization of concrete was primarily to reduce cement, which was the costliest component in concrete and the largest contributor to carbon dioxide emissions. The need to reduce cement gave rise to different particle packing theories [1]. The philosophy behind these particle packing theories was to pack the aggregates in such a way that they revealed fewer voids. Due to fewer voids, the cement required to fill up the voids was less leading to a greater density and greater compressive strength. The role of cement in this packing was to only bind or adhere the aggregates to one another. This was the main philosophy behind the particle packing theories. Over the course of time, numerous theories and models were evolved which were improved based on the previous theory. One of the models namely the Modified Andreassen model found its application in the precast industry and is being used nowadays for the packing of aggregates. Based on the Modified Andreassen curve various softwares like EMMA and LISA were developed recently which helped in proportioning the concrete.

Quartz, a white crystalline material has now found its application in the precast industry. The architects nowadays require white-colored external facades made purely of concrete. The standard concrete with basalt aggregates cannot impart the requisite white color. Hence it was important to substitute the basalt aggregates with such a material that gives the same crushing strength and imparts white color also. As quartz possesses these properties, it is now commonly used in the precast industry. The issue of achieving higher strengths is resolved by appropriately packing the aggregates by using a model like the Modified Andreassen model. Researchers have proven that such an optimized packing theory has proven to be effective in achieving higher strengths. It has also proven to be effective in reducing the voids and increasing the density of the concrete.

Literature review

Many researchers developed different aggregate packing theories and models because the aggregates comprised of 70 - 80 % of the volume of concrete. If the major part was optimally packed with fewer voids there would be a steep increase in the density. Three major factors that affected the packing of the aggregates were (i) particle shape, (ii) particle size distribution and (iii) method used for packing the aggregates. Therefore, there was a need to optimize the aggregates which in turn would lead to optimizing the overall concrete. The main objective of developing these packing theories and models was to reduce the voids, increase the density, reduce the cement content and increase the rheological properties of concrete. The first model was developed in 1928 by Furnas during his study on the movement of gases across the beds of split solids. Based on the limitation many other theories and models like Aim and Goff model, Modified Toufar model, Linear Packing density model, Compressible packing model and Solid Suspension model were developed. These models were developed based on the limitation of the previous models.

Test results of concrete mixed by Solid Suspension Model designed by de Larrard showed that flowable concrete could be created at a low water-cement ratio of 0.14. By normal steam curing with normal pressure and temperature of about 90 °C compressive strength of about 236 MPa was achieved in 28 days. Fine sand was used in this mix which was 813 kg/m^3. Cement was 1,080.6 kg/m^3. Silica fume was 334.6 kg/m^3. Water was 198.2 kg/m^3. The tensile splitting strength after 28 days was 6.6 MPa which was better than normal concrete [1]. The maximum density gradation curves, well known as the ideal curve for Fuller, were proposed by Fuller and Thomson [2].

Curve-based mix configuration equations are still used today. Some researchers have proposed the use of exponent ‘q’ within the 0.33 - 0.50 range. It was important to experimentally establish the modification factor ‘q’ and could therefore vary based on the characteristics of the particles. The ideal curve with angular coarse particles with a lower ‘q’ value should be better prescribed, as it is important to add more fine particles to fill the voids between the coarse particles [3].

Fuller in his article “The law of proportioning concrete” had carried out a huge number of experiments on ‘Jerome’ stone and ‘Cowe Bay’ sand before arriving at the equation for the smooth ideal curve. The equation was empirical and fits practically for the mixes. He proposed if the ideal curve was followed then that curve would give the maximum theoretical density which would make the concrete a dense mix. The distribution modulus ‘q’ is the ratio of aggregate to cementitious paste. As the distribution modulus is reduced up to 0.25 the sand becomes finer and the mix becomes denser. Strengths increased exponentially as the distribution modulus was reduced. But as the sand became finer the water demand increased. So, the paste required to pack the aggregates was increased. This was also observed in an article written by Raj *et al.* [4] where the strengths achieved by the normal mix were less than the strengths achieved by the packing density method. However, the main limitation of Fuller as well as Andreassen considered that the smallest size of the particle used in the mix was infinitesimally small.

In 1980, Funk and Dinger agreed that every distribution of real size must have a finite lower limit. Their optimal size distribution, contrary to the Fuller curve, paid attention not only to the largest grain but also to the smallest used grain. The ideal curves mentioned by Fuller Thomson, Andreassen, and Funk and Dinger are compared in **Figure 1**. The figure shows that the Andreassen and Funk and Dinger curves are steeper than the Fuller Thomson curve. The coarse mix with more voids is created with the Fuller Thomson curve whereas the Andreassen curves give more homogeneous mixes with a lesser number of voids.

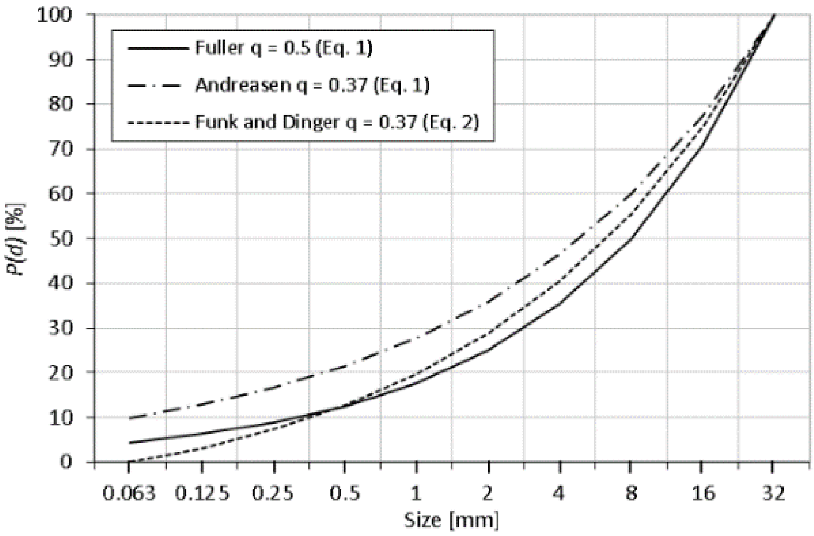


Figure 1 Ideal curves by Fuller, Andreassen, and Funk and Dinger from 32 mm maximum diameter to 63 μm minimum diameter [5].

This model is based on a continuous approach. The model that Funk and Dinger changed [6] can be described as follows:

$$Pt = \frac{d^q - dmin^q}{dmax^q - dmin^q}$$

where *Pt* is less than *d* for the fraction of total solids, *dmax* shows the maximum particle size (100 % passing), *dmin* is the particle's minimum size, and *q* is the distribution modulus.

Andreasen limited the distribution modulus to a range of 0.33 - 0.50 since fine particles did not pack the way coarse particles packed the matrix [7]. The curve that Funk and Dinger created is known as the Modified Andreassen curve. The first curve was created by Fuller with a distribution modulus of 0.5. Andreassen reduced it to 0.37. Later on, Funk and Dinger made changes in the equation and used 0.37 as the distribution modulus. The key drawback of this model is that it is based only on the distribution of particle size, and does not take into account the aggregate shape and texture.

Andreassen Model has recently been used in the production of the Ultra-High-Performance Concrete (UHPC). The distribution modulus is so adjusted that even with the use of coarser aggregates SCC mixes can be created. Some researchers created high strength concrete by packing the quartz aggregates with the Andreassen model. In Beijing, the High-pressure pipes of concrete were created using the Andreassen Model. In some researches, the geopolymer textile was used to create a dense mix where this model was used. In one of the research, the compressive strength achieved on the 28th day by using the Andreassen curve was 61.7 MPa and flexural strength achieved was 63 MPa [8]. Companies like DUCTAL have been successful in using this curve and achieving higher strengths up to 200 MPa [9]. The modern-day softwares like EMMA software and LISA software are developed based on the mathematics and particle packing philosophy of Andreassen and the Modified Andreassen curve. The aforementioned softwares are developed by ELKEM company. These softwares are used for the optimization of the concrete [10].

Certain researchers observed that the compressive strength had no change even when a part of cement was replaced by silica. Foundry sand is a waste material that is used for creating concrete. A part of crushed sand was replaced by silica sand and strength increased by 10 MPa than the normal concrete [11]. In another research, geogrid panels were cast using quartz sand. The panels were cured by the method of autoclaving. The compressive strength attained on the 28th day was 36.41 MPa. The panels were also subjected to a split tensile test in which the strength of the panel was 3.76 MPa. The flexural strength achieved on the 28th day was 10.98 MPa. Silica fume and quartz sand were used in the mix which enhanced the strength of the panels [12].

Yet another study has also shown that the use of a combination of silica fume and quartz powder as a cement replacement improves compressive strength. Splitting tensile strength improved by 20 %. The permeability of the mixes had a great reduction of up to 20 % [13]. Based on the literature review conducted, it is evident that the Andreassen model has displayed good results in creating High-performance concrete. This model has helped in creating denser mixes which further have led to higher compressive strengths. Some researchers have also shown that the cement proportion, costly material in the concrete was reduced significantly using the Andreassen model, leading to cost optimization [14].

Materials and methods

Mix design concept and EMMA software

Mix design concept

The method of proportioning the mixture comes down to the art of managing multiple conflicting requirements [15]. For appropriate proportioning of the concrete mixtures in India, Indian Standard codes have been designed which act as guidelines for initial mix proportioning. These IS codes are not statutory documents but provide recommendations that are not legally mandatory. They provide fundamental principles and basic knowledge about concrete as a subject. These IS codes are the collection of theory, databases, statement of practice and information required by the users. The IS codes like IS 10262:2019, SP 23 serve as guidelines during actual mix proportioning. The optimum proportioning of materials like silica fume, cement, aggregates and pozzolanic materials is possible with the help of the aforementioned IS codes. It is very much advisable to start trials on the materials and concrete by following the IS code provisions to get detailed information about the rheological properties of concrete and the behavior of the materials.

EMMA software

The Elkem Material Mix Analyser (EMMA) software is developed by the ELKEM company. Elkem is constantly working on improving activities and reducing the carbon footprint. Safe access to high-grade raw materials and large energy recovery investments are the ways Elkem is working to achieve this feat. The algorithm of the software is based on the Andreassen and Modified Andreassen curve. EMMA is a program that measures the distribution of particle sizes of a component mixture and shows it. Initially, it was built at Elkem to design self-flowing refractory castable compositions. EMMA is convenient-to-use computer software that enables individuals to optimize their concrete mix designs and refine them. The consumer adds sand, gravel & cementing materials to the Particle Size Distribution (PSD) and EMMA determines the perfect combination of those materials to make the best concrete. The system accommodates the full range of concrete types: Self-compacting and ultra-high-performance concrete compacted to roller. The consumer will create his own library of particle size distributions for various materials. The measurement of the distribution of particle size can be performed with any combination of these materials. After the quantity of the individual materials has been entered, the distribution is given in numbers as well as shown in a graphical format. The graph is correlated with the model of Andreassen. EMMA is the successor to a software package called Size Dist, which only runs on x-l. Edition 5.0, English Edition. EMMA is called language-independent software. The learning of this software is very much important as the same software is used for particle packing and optimization of concrete. The software is user friendly and easy to learn.

Research methodology

The main objective of the present research was to check the change in density and compressive strength of concrete by using the EMMA software based on the Modified Andreassen curve. The experimental work for the research was carried at an industry named ‘Concrete Solutions’, located in Pune. It is a precast factory that manufactures decorative external facades made of concrete. Quartz was used prevalently in the factory for the manufacturing of white external decorative fins. There was a need to increase the strength of concrete made of quartz aggregates as it exhibited lower strengths than concrete made of basalt aggregates. The experiments were carried out using quartz aggregates. The preliminary tests were taken on the materials which were available at the site. These tests proved to be helpful in knowing the properties of the materials which were used on site.

Preliminary tests conducted on-site

Preliminary tests like water absorption test, specific gravity, sieve analysis and impact value were carried out on the aggregates. The Marsh Cone test was conducted to check the compatibility of admixture with cement. The specific gravity of the admixture was measured which was essential in the concrete mix design.

Sieve analysis

The quartz aggregates were present in different bags of specific gradations. The bags were marked by their specific sieve number. The bags which were present on site were 16 - 30, 30 - 80, 80 - 100 and 300 bag. The 16 - 30 bag denoted that the bag contained aggregates ranging between the sieve number 16 and sieve number 30. There was a need for a detailed sieve analysis test of each bag. The sieve analysis later helped in the proportioning of concrete according to the Modified Andreassen curve. The sample of sieve analysis for 16 - 30 bag is shown in **Table 1**.

Table 1 Sieve analysis of 16 - 30 Quartz sand.

Sieve size (mm)	**Weight retained on each sieve (gm)**	**Percentage retained on the sieve**	**Cumulative percentage retained on the sieve**	**Cumulative percentage passing on the sieve**	
4,750	0	0	0	100	
3,350	0	0	0	100	
2,360	0	0	0	100	
1,180	2	0.4	0.4	99.6	
600	289	57.8	58.2	41.8	
300	195	39	97.2	2.8	16 - 30 Quartz sand
150	10.16	2.032	99.232	0.768	
90	3.1	0.62	99.852	0.148	
75	0.74	0.148	100	0	
45	0	0	100	0	
0	0	0	100	0	
	Total = 500	100			

Similarly, the sieve analysis of 30 - 80 and 80 - 100 bag was done to know the gradation of the aggregates in the bags and it is given in **Tables 2** and **3**, respectively. This gradation also helped in creating the mixes according to the Andreassen curve.

Table 2 Sieve analysis of 30 - 80 Quartz sand.

Sieve size (mm)	**Weight retained on each sieve (gm)**	**Percentage retained on the sieve**	**Cumulative percentage retained on the sieve**	**Cumulative percentage passing on the sieve**	
4,750	0	0	0	100	
3,350	0	0	0	100	
2,360	0	0	0	100	
1,180	0	0	0	100	
600	0	0	0	100	
300	391	78.2	78.2	21.8	30 - 80 Quartz sand
150	101.75	20.35	98.55	1.45	
90	7.25	1.45	100	0	
75	0	0	100	0	
45	0	0	100	0	
0	0	0	100	0	
	Total = 500	100			

Table 3 Sieve analysis of 80 - 100 Quartz sand.

Sieve size (mm)	Weight retained on each sieve (gm)	Percentage retained on the sieve	Cumulative percentage retained on the sieve	Cumulative percentage passing on the sieve	
4,750	0	0	0	100	
3,350	0	0	0	100	
2,360	0	0	0	100	
1,180	0	0	0	100	
600	0	0	0	100	
300	24	4.8	4.8	95.2	80 - 100 Quartz sand
150	278	55.6	60.4	39.6	
90	140	28	88.4	11.6	
75	39	7.8	96.2	3.8	
45	19	3.8	100	0	
0	0	0	100	0	
	Total = 500	100			

Impact value test for quartz

Impact value is the ability of the aggregates to withstand sudden impacts or load. This test is essential in knowing the properties of the aggregates and their resistance to sudden loading.

$$Impact\ value = \frac{B}{A} \times 100$$

$$Impact\ value = \frac{79.63}{305} \times 100 = 26.108 > 22\ \%$$

where A = weight of oven-dried sample and B = weight of fraction passing 2.36 mm IS Sieve.

The impact value of the aggregate in percentage as mentioned in the IS code should not be greater than 22 % if a high strength concrete was to be manufactured. The lesser the impact value the higher is the impact bearing resistance of the aggregates. From the above results, it was evident that the White Quartz sand had an impact value of more than 22 % which indicated that the aggregates were crushed due to sudden impact and these aggregates needed proper packing and bonding in order to manufacture a high strength concrete.

Water absorption and specific gravity test

The water absorption proved to be a pivotal test because there was a continuous variation in the water content of the concrete mix which disturbed the W/C ratio. The actual water absorption of quartz aggregates was 0.4 %. It was found out by the SSD condition test which was proposed by Utah university. The water absorption mentioned below was the total water absorption including adsorbed water. It was carried out by the Pycnometer test according to the IS code. The results of these tests are given below. Water absorption −1.01 % and Specific gravity −2.63

Specific gravity of superplasticizer

The specific gravity of the superplasticizer was 1.10. The superplasticizer was the High Range Water Reducing Admixture (HRWRA). The superplasticizer reduced 50 % of water but had little to no effect on the strength of concrete.

Marsh cone test

Marsh cone test was done to check the compatibility of admixture with the cement. This test was done for varying W/C ratios. It helped in adjusting the dosage and helped in the calculation of mix design. In this, the least time which was taken by the mixture to pass out of the funnel was 43.74 s at 1.2 %

dosage. Hence, 1.2 % was the optimum dosage of admixture in the concrete mix which would give the maximum flowability.

Normal concrete proportioning

After carrying out preliminary tests on the materials numerous control mixes were prepared using the IS code 10262:2019. W/C ratios were varied from 0.6 to 0.25. The W/C ratio of 0.25 was the last ratio mentioned in the IS code. For high strength concrete, the W/C ratio ≥ 0.25 was required. For 0.25 W/C ratio IS code provision was flexible which meant it could be followed or it could be modified by expert opinion. Expert opinion was taken and cement content was varied keeping the W/C ratio constant. The 700 kg/m^3 content of cement content gave a good strength and also good flowability when it was mixed with the fine aggregates. The W/C ratio used for the mix was 0.25. The proportion was used for the mix using White Quartz aggregates. The bags of White Quartz aggregates, used predominantly on-site, were utilized in the mix. 1 bag of 16 - 30 and 1 bag 30 - 80 were used predominantly on-site for the manufacturing of jobs. The same proportion of sand was utilized to create a normal mix using Quartz sand. The details of the mix design are mentioned in **Table 4**.

Table 4 Details of mix design by normal proportioning on 24-08-2020.

Material	Quantity in kg/m^3	For 15 cubes in kg	
Cement	700	11.9	
Water	175	2.975	
Superplasticizer	21	0.357	SP content = 3 %
16 - 30	769.275	13.077675	
30 - 80	769.275	13.077675	

Initially, the superplasticizer content for this first trial was taken as 3 % based on past experience. The mix was highly flowable. After 24 h the moulds for this mix were demoulded and it was observed that the moulds were moist and their surface was slimy and sticky. However, the moulds were set when checked physically. The strength of the moulds was checked for 1st, 3rd, 7th and 14th day. On the first day, the strength of the concrete was considerably low. This meant some revision was necessary for the design mix. According to the observations mentioned above, the mix was highly flowable. As per expert advice, the admixture content was reduced to 2 %. The same mix was again taken for the next trial but with low admixture content. The details of the mix design are given below in **Table 5**.

Table 5 Details of revised mix design by normal proportioning on 29-08-2020.

Material	Quantity in kg/m^3	For 15 cubes	
Cement	700	11.9	
Water	175	2.975	
Superplasticizer	14	0.238	SP content = 2 %
16 - 30	769.275	13.077675	
30 - 80	769.275	13.077675	

From the past literature and experience, the strength gain from the 14th to 28th day was very small as the 90 % strength gain was already taken on the 14th day. Note that this statement is only applicable for mixes having cement and no other pozzolanic material like silica fume, fly ash, metakaolin, etc. It was clearly observed that the mix was not as flowable as the previous trial. The moulds were filled and kept for 24 h. After 24 h the moulds were demoulded. The surface was free from the sticky and slimy fluid. For mixture with 3 % admixture, the first day strength was 2.67 MPa and for mixture with 2 % admixture, the first day strength was 16.387 MPa. A difference of 13.717 MPa was observed between the 2 mixes. The 2 mixes were exactly the same, but they had different admixture content.

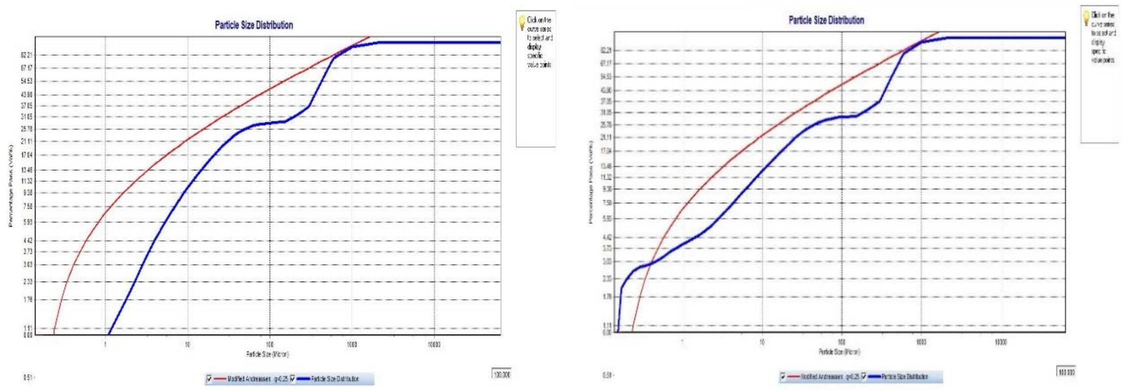
Table 6 Difference of the strength gain between the 2 mixtures.

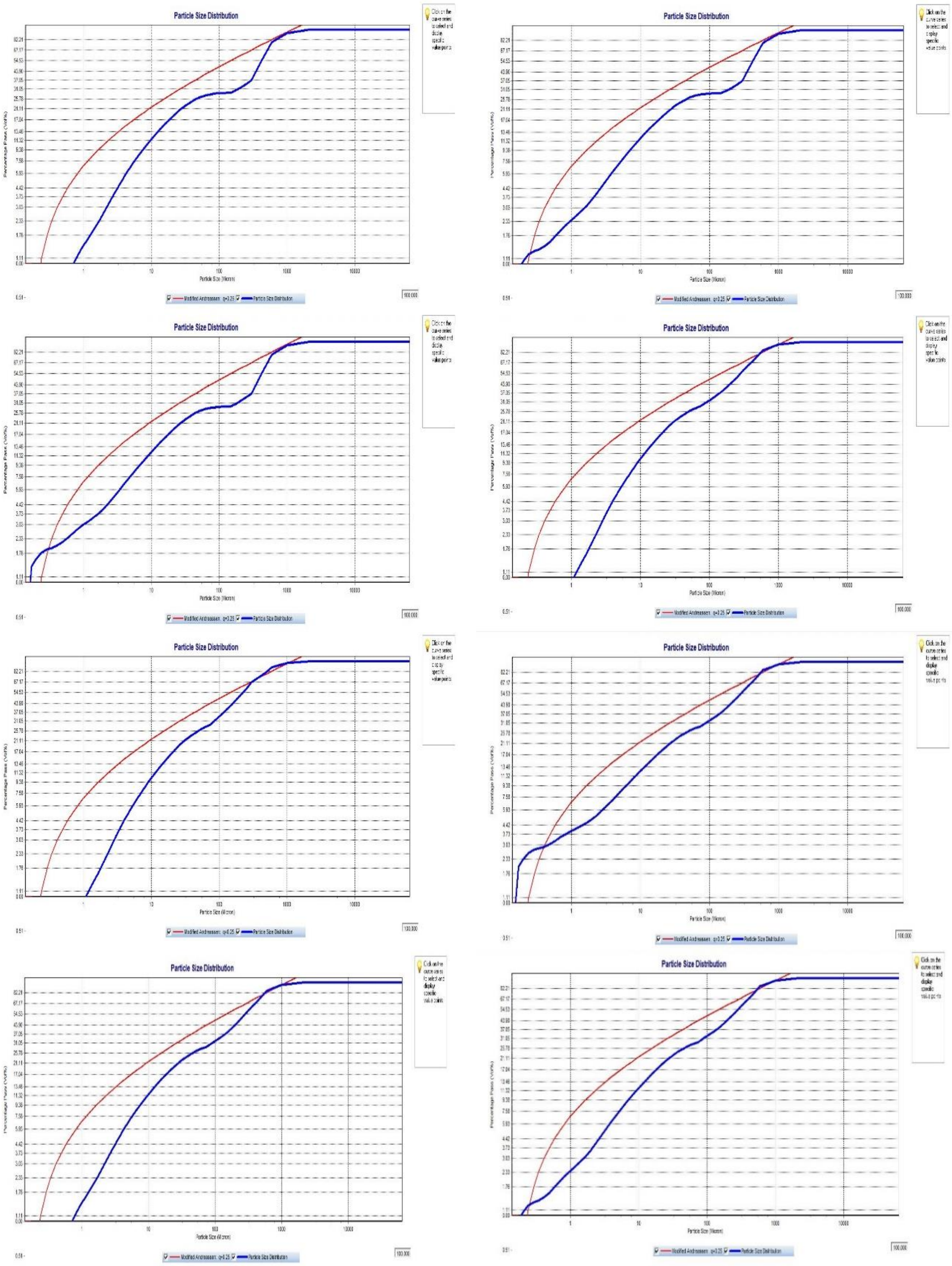
Testing day	Normal mix with 2 % admixture	Normal mix with 3 % admixture	Difference
1-day average strength	16.39	2.67	13.71
3-day average strength	42.84	24.16	18.68
7-day average strength	61.29	41.03	20.25
14-day average strength	70.55	49.01	21.54

This led to an indication that the excess superplasticizer content may have retarded the setting action. The slimy fluid was also an indication of excess superplasticizer which got adhered to the cement molecules. **Table 6** gives a detailed difference of the strength gain between the 2 mixtures. The results indicated that there was a difference in the strength gain if the admixture content was varied. The 14^{th} day average strength achieved by the mix with a 2 % admixture was 70.55 MPa. The 14^{th} day strength of the normal mix with 2 % admixture was 70.55 MPa which was acceptable as the strength was going to increase on the 28^{th} day. However, the strength gain would be in a small increment.

Proportioning of concrete by using EMMA

The strength gain of the mixes by normal proportioning was within limits according to the IS code but the strength could be improved for the same mixes by packing the materials better using the Andreassen model. As mentioned earlier the EMMA software was used to optimize the same mixes which are explained above. EMMA program was used to optimize the mixes. It was necessary to conduct different trials and combinations in order to achieve an optimum packing curve. The existing curve was checked in the EMMA software and then a few trials were conducted on the software. The trials were carried out in a systematic order by introducing 1 material at a time for every trial. The trials conducted in EMMA software are shown below in **Figure 2**. The main objective of using EMMA software was to reduce field trials. The objective for conducting the trials in EMMA was to get the actual distribution curve denoted by a blue curve as closely as possible to the ideal curve which was denoted by a red curve. In the first trial, as shown in the figure, the blue curve was far away from the red curve. The objective was to get the blue curve as close as possible to the red curve to achieve the optimum packing density. The materials were added to the mix in a systematic order that is 1 material at a time for a single trial. This was done to check the effect of the material on the mix. Many combinations were used for the trials. The silica fume and the metakaolin were varied from 8 to 16 %. The quartz aggregates fillers namely 80 - 100 bag and 300 sieve number bag were used in the software to check whether they affect the practical particle size distribution curve. Trial 12 showed the best results out of all the trials conducted in the EMMA software. The flow chart shows that for Trial 12 the mix had closely matched with the ideal curve.




Particle Size Distribution
Particle Size Distribution
Particle Size Distribution
Particle Size Distribution
Particle Size Distribution
Particle Size Distribution
Particle Size Distribution
Particle Size Distribution

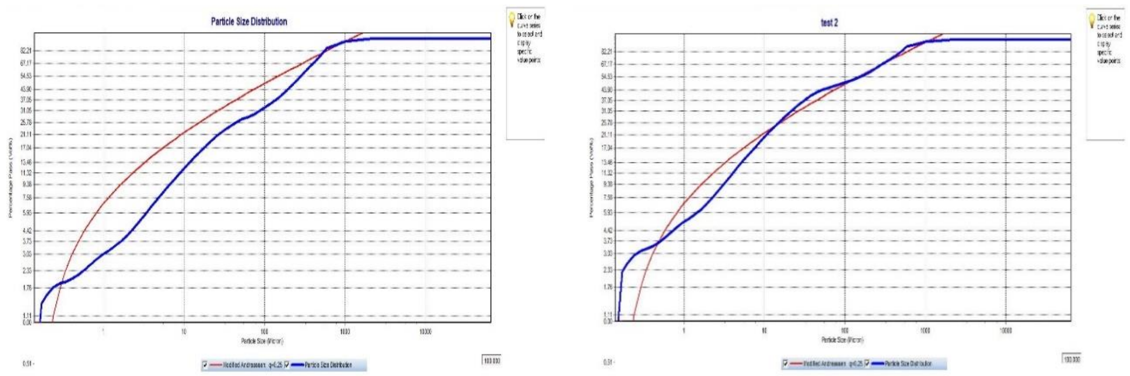


Figure 2 Trials conducted in EMMA software.

More than 20 different combinations other than these 12 trials were tried, to match the ideal curve. Out of all, Trial 12 gave the best fit for the ideal curve. The same mix was adopted as Andreassen proportioned mix to conduct practical trials. **Table 7** mentions the details of materials proportioned by using EMMA.

Table 7 Details of the materials proportioned by using EMMA on 05-09-2020.

Material	Quantity in kg/m^3	For 15 cubes	
Cement	588	9.99	
Water	175	2.98	
Superplasticizer	21	0.36	
Metakaolin	56	0.95	
Silica	56	0.95	SP content = 3 %
16 - 30 Quartz	384.64	6.54	
30 - 80 Quartz	384.64	6.54	
80 - 100 Quartz	384.64	6.54	
300 Quartz	384.64	6.54	

Initially, a dosage of 2 % was added to the mix. The materials were not getting homogeneously mixed. To counter that problem 1 % extra admixture was added after 15 min of mixing. The mix was filled into the moulds and was allowed to set for 24 h. There was a very little amount of slimy fluid on the surface of the mould but not like the normal mixture of concrete with a superplasticizer content of 3 %. The first day strengths achieved were not that significant as expected. When the results of the Andreassen mix with 3 % superplasticizer were compared with Normal concrete with 2 % superplasticizer and Normal concrete with 3 % superplasticizer the results on day 1 and day 3 were not as per expectation. It was envisaged that the Andreassen proportioned mix would take exceptional strengths right from day 1 But this was not the case, the strengths of the Andreassen mix were almost close to the strengths achieved by Normal concrete with 2 % superplasticizer. After analysis of the results of day 1 and day 3, it was interpreted that the extra admixture retarded the setting time which led to late strength gain. On the 14th day, the average strength achieved by the concrete was 79.09 MPa which meant that the strength gain was exceptional after the 7th day strength.

It was also observed that the change in density was more significantly seen in Andreassen proportioned concrete than the normal concrete. The surface had lesser pores as compared to the normal concrete which also meant that the concrete was appropriately packed. The additional 1 % led to retardation and late strength gain but it was necessary as the mix was required to be flowable. The same mix was going to be utilized in the textile-reinforced concrete and the opening of the TRC sheet was very small. Therefore, the concrete was made flowable by adding an extra 1 % of superplasticizer.

A final trial was conducted on the same mix but with 2.5 % superplasticizer. This trial was conducted because the 1st, 3rd, and 7th day strengths of the previous trials were not satisfactory, even though the 14th day strength was significantly high. The details of the final trial conducted on-site are given below in **Table 8**.

Table 8 Revised details of materials proportioned by EMMA on 11-09-2020.

Material	Quantity in kg/m^3	For 15 cubes	
Cement	588	9.996	
Water	175	2.975	
Superplasticizer	17.5	0.2975	
Metakaolin	56	0.952	
Silica	56	0.952	SP content = 2.5 %
16 - 30	384.638	6.538846	
30 - 80	384.638	6.538846	
80 - 100	384.638	6.538846	
300	384.638	6.538846	

For this trial, only a 2 % admixture was added initially for the mix. The mixing was done for 15 - 20 min and the mixture was still not properly mixed. An additional dose of only 0.5 % was added to the mix. Also, the mixing blade was small and the mixing drum was too large. Due to this, the concrete mixed homogeneously in one area and the other areas were left unmixed. This led to a condition where the mix was not homogeneous and usually in such conditions, the additional admixture is added. In the previous mixes if the mixing time was increased from 15 to 40 min then additional admixture would have not been required in the mix. This may have not retarded the setting and strength gain would have been better. Nevertheless, the strength gain for this trial was satisfactory as the 1st day strengths of this mix exceeded all the other mixes. The moulds were filled and kept for 24 h and then demoulded. The average strength which was achieved on the 14th day was 96.18 MPa. The highest strength reached on the 14th day was 100.05 MPa. Altogether, the concrete which was created in the last trial showed good results.

Results and discussion

There were some interesting findings when the concrete was proportioned using Quartz aggregates. Basically, the 2 methods of proportioning were compared using Quartz aggregates. Four mixes were prepared for a comparative analysis of the aggregates. Two mixes were normal proportioned concrete with 2 and 3 % admixture. The other 2 mixes were proportioned using the Andreassen curve with 2.5 and 3 % admixture. The 4 mixes were compared based on the strength gain and change in density. The comparative analysis of the 4 mixes based on strength is given in **Figures 3** and **4**.

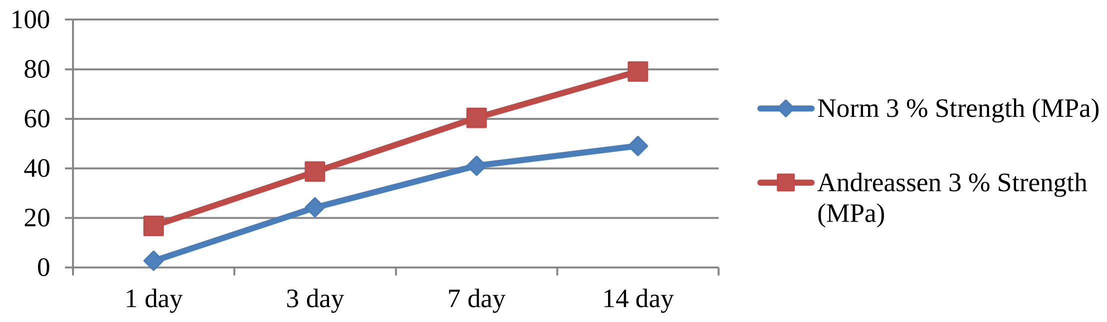


Figure 3 Comparison between Andreassen proportioned concrete and Normal concrete with 3 % admixture.

From the graph, it is evident that the Andreassen proportioned concrete imparted more strength than the normal concrete. If the 7th and 14th day strength of the normal concrete is taken into consideration then the strength gain reduced from the 7th to 14th day. The drop in strength gain could be seen which is indicated by a blue curve in **Figure 3**. Whereas the Andreassen proportioned concrete did not show a drop in the strength gain from the 7th to 14th day. The graph of Andreassen proportioned concrete was almost linear. There was no significant drop in strength gain. The average strengths are plotted on the graph shown in **Figure 3**. The strength achieved on the 14th day by Andreassen proportioned concrete was 79.09 MPa. Whereas the strength achieved by normal concrete on the 14th day was 49 MPa.

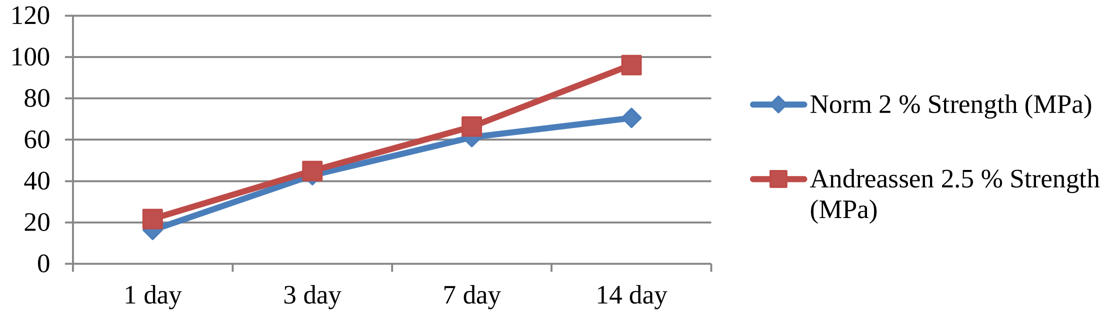


Figure 4 Comparison between Andreassen proportioned concrete with 2.5 % admixture and Normal concrete with 2 % admixture.

From **Figure 4** it was clear that the strengths achieved by Andreassen proportioned concrete were high but there was no significant difference in the strengths of normal concrete and Andreassen proportioned concrete on 1st, 3rd and 7th day. However, the difference was seen on the 14th day where the strength exponentially increased for the Andreassen proportioned curve. The strength achieved on the 14th day was 96.18 MPa. Whereas the strength achieved for normal concrete was 70.55 MPa. This led to an interpretation that the silica fume and metakaolin did not impart strength for the first 7 days. They remained inert materials until the hydration process took place. The water reacted with cement first and then the compound reacted with metakaolin and then with silica fume. The silica fume and metakaolin acted as fine reacting materials. These materials helped impart later age strength. The early age difference between the Andreassen proportioned concrete and normal concrete was small because the silica fume and metakaolin were replaced in the cement. Therefore, the W/C ratio increased as the cement content was reduced. The W/B (water/binder) ratio however remained the same for the mix. There was also a significant change in the density of the concrete. The comparative analysis of the 4 mixes based on density is given in **Figures 5** and **6**. The change in the density of the concrete was tracked for all the 4 mixes. The results are shown below. The graphs mentioned below in **Figures 5** and **6** show the increase in density from day 1 to the respective day. For example, as shown in **Figure 5** the increase in density on the 3rd day as compared to the 1st day was by 12.16 kg/m^3 for Andreassen proportioned concrete. But the increase in density on the 3rd day as compared to the 1st day for normal concrete was 7 kg/m^3. The graph depicts the increase in the density on that particular day of testing as compared to the density on day 1. The Andreassen proportioned concrete showed more increase in the density as compared to the normal concrete. The total increase in density for Andreassen proportioned concrete on the 14th day was 18 kg/m^3, whereas the total increase in density for normal concrete on the 14th day was 13.16 kg/m^3. From this graph, it could be concluded that the voids were filled up and the porosity was reduced because of the silica fume and metakaolin content in Andreassen proportioned concrete. The voids were filled up which led to an increase in the density.

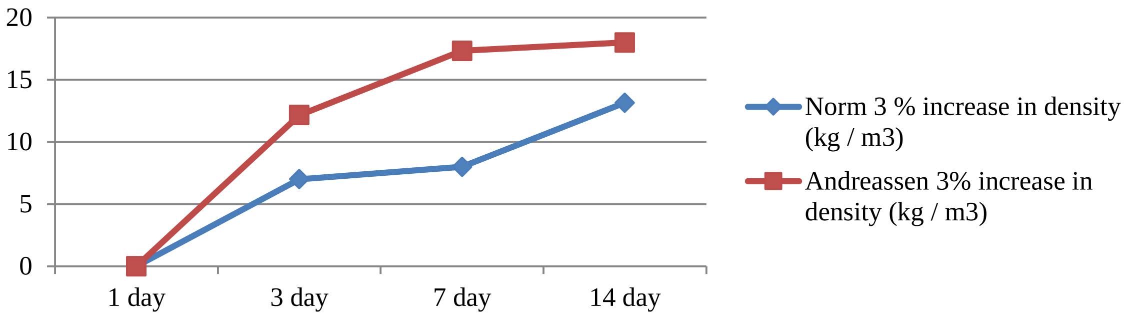


Figure 5 Comparison of increase in density between Andreassen proportioned concrete and Normal concrete with 3 % admixture.

Figure 6 illustrates the graphs of Andreassen proportioned concrete with superplasticizer content of 2.5 % and normal concrete with superplasticizer content of 2 %. The increase in density of the Andreassen proportioned concrete was more than the normal concrete. The total increase in density for Andreassen proportioned concrete on the 14^{th} day was 16.67 kg/m^3, whereas the total increase in density for normal concrete on the 14^{th} day was 11.67 kg/m^3. The Andreassen proportioned concrete showed better packing than the normal proportioned concrete. The strength of the Andreassen proportioned concrete was also better than the normal concrete. Better packing of particles was perceived in the Andreassen proportioned concrete than the normal concrete.

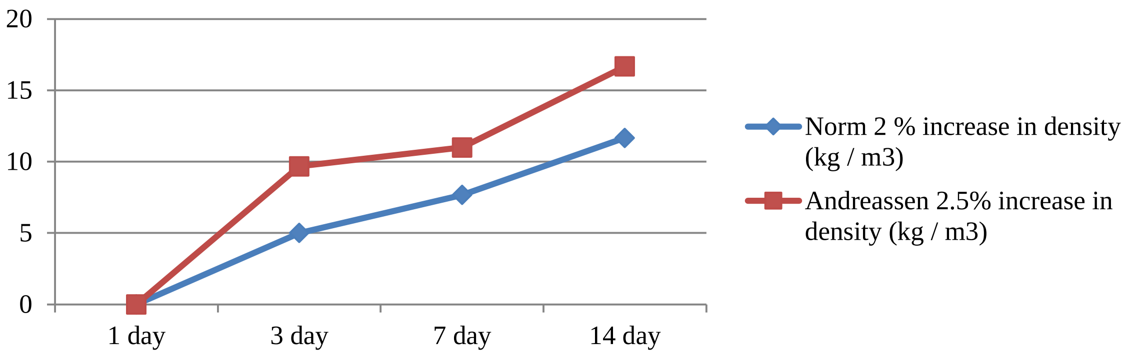


Figure 6 Comparison of increase in density between Andreassen proportioned concrete with 2.5 % admixture and Normal concrete with 2 % admixture.

Conclusions

The silica fume packed the finer fraction from 0.1 to 1 μ whereas the metakaolin somewhat packed the finer fraction from 1 to 10 μ. The coarser fraction was packed by 80 - 100 i.e. sieve size varies from 80 to 100 aggregates. The main limitation of this software was that different combinations had to be tried for getting closer to the ideal distribution curve. The software computed the difference of the mix from the ideal mix but it did not compute the particles lacking in the mix. The q-value played a pivotal part in setting the slope for the ideal curve. The modified Andreassen curve was more effective in optimizing the mixes than the Andreassen curve. The use of software led to the optimization of cement by 16 % where cement was replaced by 8 % metakaolin and 8 % silica fume. The software was useful in eliminating the number of trials. The trials could be performed without wasting any materials on site. Altogether the software was very useful yet many improvements were essential to make it a more effective software. The Andreassen proportioned concrete showed better packing than the normal proportioned concrete. The strength of the Andreassen proportioned concrete was also better than the normal concrete. The silica fume and metakaolin did not impart strength for the first 7 days. They remained inert materials until the hydration process took place. The water reacted with cement first and then the compound reacted with metakaolin and then with silica fume. The silica fume and metakaolin acted as fine reacting materials.

These materials helped impart later age strength. The early age difference between the Andreassen proportioned concrete and normal concrete was small because the silica fume and metakaolin were replaced in the cement. Therefore, the W/C ratio increased as the cement content was reduced. The W/B (water/binder) ratio however remained the same for the mix. There was also a significant change in the density of the concrete.

Acknowledgments

We are greatly in debt to Dr. Sayali Sandbhor, Assistant Professor, Department of Civil, Symbiosis Institute of Technology, Symbiosis International University, Pune, India who suggested corrections in the research paper and helped in improving the quality of the research paper.

References

[1] FD Larrard and T Sedran. Optimization of ultra-high-performance concrete by the use of a packing model. *Cement Concr. Res.* 1994; **24**, 997-1009.
[2] WB Fuller and SE Thomson. The laws of proportioning concrete. *Trans. Am. Soc. Civ. Eng*. 1907; **59**, 67.
[3] SV Kumar and M Santhanam. Particle packing theories and their application in concrete mixture proportioning: A review. *Indian Concr. J.* 2003; **77**, 1324-31.
[4] N Raj, SG Patil and B Bhattacharjee. Concrete mix design by packing density method. *IOSR J. Mech. Civ. Eng.* 2014; **11**, 34-46.
[5] SAAM Fennis and JC Walraven. Using particle packing technology for sustainable concrete mixture design. *Heron* 2012; **57**, 73-101.
[6] M Mangulkar and S Jamkar. Review of particle packing theories used for concrete mix proportioning. *Int. J. Sci. Eng. Res.* 2013; **4**, 143-8.
[7] C Gong, J Zhang, S Wang and L Lu. Effect of aggregate gradation with fuller distribution on properties of sulphoaluminate cement concrete. *J. Wuhan Univ. Tech. Mater. Sci.* 2015; **30**, 1029-35.
[8] G Hüsken and HJH Brouwers. A new mix design concept for earth-moist concrete: A theoretical and experimental study. *Cement Concr. Res.* 2008; **38**, 1246-59.
[9] NM Azmee and N Shafiq. Ultra-high performance concrete: From fundamental to applications. *Case Stud. Constr. Mater.* 2018; **9**, e00197.
[10] C Emma and S Distribution. *User guide Elkem materials mixture analyser - EMMA.* Elkem, p. 35.
[11] JL Chaudhary, A Harison and V Srivastava. Use of silica sand as cement replacement in ppc concrete. *Int. J. Res. Eng. Tech.* 2015; **4**, 55-8.
[12] R Roy and V Sairam. Effect of silica fume and foundry waste sand on strength characteristics of Geogrid and Ferro cement panel. *Mater. Today Proc.* 2019; **7**, 362-72.
[13] A Nikdel. 2014, Mechanical properties of concrete containing quartz powder as a filler instead of using silica fume. Master Thesis. Eastern Mediterranean University, Gazimağusa, North Cyprus.
[14] PHR Borges, LF Fonseca, VA Nunes, TH Panzera and CC Martuscelli. Andreasen particle packing method on the development of geopolymer concrete for civil engineering. *J. Mater. Civ. Eng.* 2014; **26**, 692-7.
[15] PK Mehta and PJM Monteiro. *Concrete microstructure, properties, and materials*. McGraw-Hill Education, New York, 2014.