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Link of Self-Compacting Fiber Concrete Behaviors to Composite Binders and Superplasticizer

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Abstract

Composite binders were prepared as novel compositions, on the basis of which fiber reinforced self-compacting concretes (FRSCC) with high rheological, mechanical, dynamical, and impermeability behaviors are created. Rice husk ash, quartz sand, and limestone crushing waste within CEM I and different ratio of superplasticizer were investigated as components of composite binders. Central Composite Face Centered method was used to design the number of experiments and randomizations and then screened by Response Surface Methodology. The validity of models was projected by ANOVA. Replacement of cement by waste composite binders as a supplementary cementitious material has a positive effect on mechanical properties of FRSCC from 30% to around 35% of cement replacement. Adding the superplasticizer improved the performance of FRSCC in all aspects in the given range. Increasing the waste composite binders decreased the vapor permeability and effective diffusion coefficient of FRSCC by improving the hydration rate and decreasing the pores of the concrete matrix. Designed FRSCC has the potential to be used as a material for protective structures, because it is able to provide comprehensive protection against the dynamic effects and penetration of gases.

Introduction

Effective concretes for protective structures in connection with the increasing number of natural and man-made disasters, as well as heightened international tensions, are now of particular importance (Murali and Ramprasad 2018; Fediuk et al. 2018a; Yoo et al. 2016; Aly et al. 2019; Matias et al. 2013). These concretes require a special set of characteristics, i.e., compressive strength and tensile strength (Evelson and Lukuttsova 2015; Topçu and Uygunolu 2010; Yu et al. 2018), impact strength (Neville and Brooks 2010; Mahakavi et al. 2019), dynamic strength (Kim 2019; Bir Singh et al. 2019), crack resistance (Fediuk et al. 2018b; Elgalhud et al. 2017), impermeability (Fediuk et al. 2019; Lye et al. 2015) and workability (Chithra et al. 2016; Pan et al. 2018). Designing materials that can provide a set of these characteristics at a given level is possible only with the use of the latest advances in building materials science and the management of structure formation processes through the use of multicomponent systems (Artamonova et al. 2017; Fediuk et al. 2017; Asaad et al. 2018; Mosaberpanah and Eren 2016; Lesovik et al. 2018).

At the same time, concern for human life and health from the standpoint of the “man material habitat” system should be taken into account even at the material production stage. Reducing the consumption of clinker raw materials and the energy intensity of manufacturing materials, as well as the utilization of industrial waste are essential steps along this path (Loganina and Ryzhov 2015; Sprince et al. 2016; Rich et al. 2017). Extreme natural and man-made impacts on structures were considered by Birbraer and Shulman (1986), and Nazmeeva and Vatin (2016). The radiation protection of various structures has been studied in considerable detail (Ibragimov et al. 2019; Aslani 2013). A number of concretes have been developed for various heavyweight aggregates such as serpentinite, magnetite, hematite, etc. (Ibragimov et al. 2019; Smirnov et al. 2017). The protection of structures against high temperatures and fire has been investigated by Khezhev et al. (2018), Khoury (2002), Kodur and Sultan (2003) and Donatello et al. (2014).

De Sensale and Viacava (2018), Fediuk et al. (2017, 2018a, 2018b, 2019), as well as the Geomimetics Scientific School (Lesovik et al. 2018, 2019) were engaged in increasing the strength and impermeability of structures. It is proved that the creation of high density and high strength composites is possible only due to the synergistic effect of organic and mineral additives, as well as through the management of structure formation at the nano-, micro- and macro-levels. The paper of Erofeev et al. (2016) is dedicated to protection against biological effects. Seismic resistance of buildings and structures were considered by Graybeal and Baby (2013) and Arya...
At the same time, the study of defensive structures against the complex of the damaging effects of modern means of warfare, as well as natural and man-made disasters was not made.

In previous studies (Fediuk et al. 2018a; Evelson and Lukuttskova 2015; Yu et al. 2018), theoretical foundations were developed for creating composite binders (CB) using various pozzolanic additives and silica-containing components, as well as concrete based on composite binders, natural and man-made aggregates and disperse reinforcement. However, the issue of using new types of ultra-fine mineral additives, as well as the principles of their compatibility to ensure the required performance characteristics of CB, is not well understood. It is necessary to develop composites of a new generation, which are characterized by a special set of required high rates of physical and mechanical properties: dynamic strength, compressive strength, tensile strength, elastic modulus and vapor/gas impermeability.

Composite binder is a mix of hydraulic binder, silica-containing component and various modifiers that help to optimize the specified characteristics of the final products. By the current time, a rather significant number of various composite binders have been developed and tested, unique both from the standpoint of environmental protection, and profitable in terms of capital investments, as well as manufactured and tested on an industrial scale. At the same time, knowing all the advantages of such compositions, due to the effect of various factors, these composites do not have a deserved volume of production capacity at cement and concrete plants and sales markets (Yoo et al. 2016; Aly et al. 2019; Topçu and Uygunolu 2010).

An effective method is the use for the materials of protective structures a fiber reinforced concrete, which potentially has a high impact resistance (Klyuev et al. 2018; Lesovik et al. 2018; Urkhanova et al. 2018; Fediuk et al. 2017, 2018a, 2018b, 2019; Abrishambaf 2017; Yoo 2016). The distribution of stresses in the concrete matrix, provided by the dispersion reinforcement leads, to a certain extent, to the growth of the whole complex of physical and mechanical properties and performance characteristics of the composite: both compressive and tensile strengths, crack resistance, impact endurance (Lesovik et al. 2019; Ganesh et al. 2018).

Thus, it seems expedient to develop self-compacting fibrous concretes with a view to increasing their efficiency through the use of promising binder composites using production wastes. The scientific significance of paper lies in the development of fibrous concretes on the composite binders that can be used for the construction of the protective structures.

### 2. Materials and experimental methodology

#### 2.1 Materials

**Table 1 Chemical composition of the components of CB (%).**

| Component                        | CaO | SiO₂ | Al₂O₃ | Fe₂O₃ | MgO | SO₃ | Na₂O | K₂O | TiO₂ | LOI |
|----------------------------------|-----|------|-------|-------|-----|-----|------|-----|------|-----|
| CEM I                            | 66.2 - 67 | 20.2 - 20.9 | 6.0 - 6.7 | 3.5 - 4.0 | 1.4 - 2.0 | - | - | - | - | 0.18 |
| RHA                              | 0.56 | 94.48 | 0.22 | 0.11 | 0.23 | 0.05 | 0.27 | 0.26 | - | 3.82 |
| Quartz sand                      | 0.015 | 99.48 | 0.254 | 0.128 | - | - | 0.04 | 0.073 | - | - |
| Limestone crushing waste         | 44.21 | 7.49 | 3.33 | 0.24 | 2.57 | - | - | - | 0.24 | 38.71 |

**Table 2 Mineralogical composition of the used CEM I (%).**

| C₂S | C₃S | C₃A | C₄AF |
|-----|-----|-----|------|
| 58 - 67 | 8 - 15 | 10 - 12 | 10.5 - 12.5 |

**Figure 1 Composite binder design.**

When designing a binder composite, limestone crushing waste from the Dlinnogirskiy deposit (Russia) was used. The following minerals represent the mineral composition of the microfiller used: organic limestone dolomitic, crystalline variegated (2 to 25%), mixed with up to 20% phosphate and 2 to 3% rare quartz grains. Properties of LCW are given in **Table 4**. According to the results of XRD analysis, the limestone microfiller contains 98.8% of calcite and 1.2% of quartz (Fig. 4).
Sand of Razdolnensky deposit (Russia) was used as a silica filler. The particle size of silica sand is given in Table 5. The microstructure of particles of fine quartz sand (Fig. 5) shows a sufficiently developed surface of the particles. Fine quartz sand as microfiller has low water absorption and high resistance to aggressive media, and is therefore well suited for use in self-compacting protective concrete. The density of fine quartz sand is 2650 kg/m³. The specific surface area is 290 to 500 m²/kg, depending on the fraction, the pH is 7 and loss on ignition is 0.12. The specific surface area of raw materials was determined using a PSH-11 device (Russia) which operates on the principle of air permeability though a layer of the pre-compacted material.

Quartz sand from the Razdolnensky deposit is also used as fine aggregate. Its characteristics are given above.

To reduce a water / cement ratio, the Pantarhit PC 160 superplasticizer (Ha-Be Betonchemie, Germany) was used (Table 6).

Anchoring steel brass plated fibers (Universum, Russia) were used as dispersed reinforcement (Fig. 6, Table 7). Brass coating provides increased resistance to aggressive media.

### 2.2 Experimental methodology
In this study, all the experiments designed using Design of experiment (DOE). DOE is a method to find the relationship between few defined factors that are independently effective on responses or outputs by making minimum number of tests.

To monitor the effects of two variables, the central composite face centered design (CFC) was selected as CB fillers and superplasticizer (SP) on characteristics of fiber reinforced self-compacting concrete (FRSCC). CFC is composed of full factorial in two levels design (2n), besides a repetition of the nominal design, and, the 2n points found by changing one design variable at a time by an amount α = 1 to control the curvature of variable as shown in Fig. 7.

The statistical software, “Design-Expert version 10”, Stat-Ease, Inc., was used to implement and design of experiments as given in Table 8.

Modeling and analysis of results were done by using response surface methodology (RSM) which is a mixed of statistical and mathematical techniques useful for the displaying and analysis of different issues. Adequacy of models was estimated by using analysis of variance (ANOVA) which is showing the quality of selected models.

### Table 3 Physical and mechanical properties of the used CEM I (%).

| Property                        | Value       |
|---------------------------------|-------------|
| Cumulative passed through a sieve 0.08 (%) | 91.8 - 93.0 |
| Density (kg/m³)                 | 290         |
| Viscosity (%)                   | 27          |

### Table 4 Physical and mechanical properties of LCW.

| Property                        | Value       |
|---------------------------------|-------------|
| Volume weight (g/cm³)           | 2.59        |
| Porosity (%)                    | 1.37        |
| Water absorption (%)            | 1.64        |
| Abrasion (g/cm³)                | 0.97        |
| Compressive strength (kg/cm³)   |             |
| in air-dry condition            | 1200        |
| in water-saturated condition     | 940         |
| after 50 freezing cycles        | 735         |
| Softening coefficient           | 0.85        |
| No. of freezing and thawing cycles | 25         |

### Table 5 Physical and mechanical properties of the used CEM I (%).

| Property                        | Value       |
|---------------------------------|-------------|
| Volume weight (g/cm³)           |             |
| Porosity (%)                    |             |
| Water absorption (%)            |             |
| Abrasion (g/cm³)                |             |
| Compressive strength (kg/cm³)   |             |
| in air-dry condition            |             |
| in water-saturated condition     |             |
| after 50 freezing cycles        |             |
| Softening coefficient           |             |
| No. of freezing and thawing cycles |           |

### Table 6 Physical and mechanical properties of CEM I (%).

| Property                        | Value       |
|---------------------------------|-------------|
| Compressive strength (MPa)      |             |
| 1 d                             | 30.2 - 32.6 |
| 3 d                             | 40.0 - 42.2 |
| 28 d                            | 90.2 - 52.7 |
| Setting time (min)              |             |
| start                           | 112         |
| end                             | 256         |
| Cumulative passed through a sieve 0.08 (%) | 91.8 - 93.0 |
| Specific surface area, (m²/kg)  | 290         |
| Viscosity (%)                   | 27          |

### Table 7 Physical and mechanical properties of CEM I (%).

| Property                        | Value       |
|---------------------------------|-------------|
| Setting time (min)              |             |
| start                           | 112         |
| end                             | 256         |
| Cumulative passed through a sieve 0.08 (%) | 91.8 - 93.0 |
| Specific surface area, (m²/kg)  | 290         |
| Viscosity (%)                   | 27          |

### Table 8 Physical and mechanical properties of CEM I (%).

| Property                        | Value       |
|---------------------------------|-------------|
| Compressive strength (MPa)      |             |
| 1 d                             | 30.2 - 32.6 |
| 3 d                             | 40.0 - 42.2 |
| 28 d                            | 90.2 - 52.7 |
| Setting time (min)              |             |
| start                           | 112         |
| end                             | 256         |
| Cumulative passed through a sieve 0.08 (%) | 91.8 - 93.0 |
| Specific surface area, (m²/kg)  | 290         |
| Viscosity (%)                   | 27          |

### Fig. 2 SEM image of the CEM I grains microstructure.

### Fig. 3 The particle size distributions for CEM I, LCW and ASCA.

### Fig. 4 The XRD results of the limestone microfiller.
In this study, slump flow, 28 day compressive strength, tensile strength, elastic modulus, dynamic compressive strength, impact viscosity coefficient, vapor permeability, and effective diffusion coefficient properties of FRSCC were investigated by substituting of fraction CB fillers and different ratios of superplasticizer. Variable proportions are given in Table 9.

The reason for varying the amount of filler is to find the optimal percentage of replacement of cement with simultaneous increase in physical, mechanical, and exploitation characteristics of the composite. 9 batches were arranged (Table 10) at three levels of CB fillers and superplasticizer. Mixing of batches were performed follows ASTM C305-14. After preparing the mixes, they were molded and then compacted based on ASTM C109-16. Afterward compacting, they were stored for 24 hours at curing room with relative humidity of 99%. Thereafter, then all specimens were demolded and kept under saturated lime water up to the date of testing at normal room temperature.

### 2.2.1 Slump flow test of FRSCC
A rigid non-absorbing plate with 100 mm and 500 mm diameter concentric circles marked on it (Fig. 8) was used as the slump plate, together with a slump cone (ASTM C 143), a scoop for loading concrete into the cone, a stopwatch and a measuring tape (ASTM C 1611/C 1611M-05). The volume of the tested mixture was 5.6 L. The cone and plate were moistened (making...
sure that there was no standing water), the plate was placed on a solid level surface. The slump cone was centered upside down on the plate (using a 10 cm concentric circle as a guide), held tightly, and filled in one lift without any external compaction. Any excess concrete was removed from the top of the cone and any spilled concrete was removed on the slab. The slump cone was removed by raising it vertically upwards, being careful not to apply lateral or torsional movement. The time for spreading concrete to a diameter of 500 mm (T50) was measured. The final drop in flow in two orthogonal directions was measured after the cessation of the flow of concrete.

2.2.2 Compressive strength, tensile strength and elastic modulus

Compressive strength and elastic modulus measurements were performed on 100 mm cubes after 3, 7, and 28 days of curing. Tensile strength was measured on prisms with an edge length of 100 × 100 × 500 mm using four point bending with a span distance of 400 mm. All specimens were cured at a relative humidity of 50% and at a temperature of 23 ± 2°C. All tests were completed using a Shimadzu (Kyoto, Japan) Servopulser U-type servo-hydraulic fatigue and endurance tester with a capacity of 200 kN according to DIN EN 12390-3-2009.

2.2.3 Dynamic compressive strength

Two series of tests were made on the panels and cylinders. The panels (size: 600 × 600 × 50 mm) were removed from the mold after 24 hours of casting and left in the laboratory until the testing age. The impact ability of the panels was tested on the 28th day. The impact endurance test was carried out with the help of a falling hammer according to ACI Committee 544; the impact resistant specimen was subjected to repeated blows on one place. In this test, a hammer weighing 10 kg fell from a height of 600 mm on the panel. The weight of the hammer and the height of its fall were selected based on simulation of the projectile. This is due to the purpose of the study, which is to develop a material for protective structures. The impact energy was calculated according to the following Eq. (1):

\[ E_i = m \cdot g \cdot h \cdot N \]  

Table 8 Experimental design.

| Mix No. | Run | Fillers (% of CB) | Superplasticizer (% of CB) | CFC component |
|---------|-----|-------------------|-----------------------------|---------------|
| 1       | 1   | -1               | -1                          | (2n) Factorial Points |
| 2       | 6   | -1               | 0                           |               |
| 3       | 8   | -1               | 1                           |               |
| 4       | 2   | 0                | -1                          |               |
| 5       | 5   | 0                | 0                           |               |
| 6       | 10  | 0                | 1                           |               |
| 7       | 7   | 1                | -1                          |               |
| 8       | 4   | 1                | 0                           |               |
| 9       | 3   | 1                | 1                           | (2n) Axial Points |

Table 10 Specimens proportion of FRSCC.

| Sample number | Materials consumption per 1 m³ (kg) |
|---------------|-----------------------------------|
|               | Binder (kg)                        |
|               | CEM I  | Fillers of CB                  |
| 1             | 685    | 460                             |
| 2             | 685    | 460                             |
| 3             | 685    | 460                             |
| 4             | 630    | 515                             |
| 5             | 630    | 515                             |
| 6             | 630    | 515                             |
| 7             | 630    | 515                             |
| 8             | 630    | 515                             |
| 9             | 630    | 515                             |

Table 9 Range of variables.

| Variables       | Assigned | Levels of Variables |
|-----------------|----------|---------------------|
| Filler (% of CB)| A        | -1                  |
|                 |          | 0                   |
|                 |          | +1                  |
| Superplasticizer (% of CB) | B | 1.0 | 1.3 | 1.6 |

Fig. 8 The slump flow plate.
where $E_i$ is the impact energy (J), $m$ is the hammer weight (10 kg), $g$ is the acceleration due to gravity (9.81 m/s²) and $N$ is the number of blows.

The ratio of the number of blows causing failure $N_f$ to the number of blows causing the first crack $N_c$ is defined as the impact viscosity coefficient $\mu_i = N_f / N_c$. The crack width of the entire fiber reinforced concrete panel was measured using an AM3713TB (Dino-Lite, Taiwan) microscope immediately after the appearance of the first crack, and the propagation of cracks in the panel was studied.

The study of the cylinders was carried out on the same device. Dynamic strength was studied on cylinders with a diameter of 75 mm and a height of 40 mm. In the study of single blows, three different drop heights of the hummer were considered, that is, 400 mm, 600 mm and 800 mm.

### 2.2.4 Impact viscosity coefficient

The impact viscosity coefficient of the samples $\mu_i$ (J/m²) was determined as a ratio of the work expended on its destruction to the area of the sample in the plane of impact. The panels (size: 600 × 600 × 50 mm) were removed from the mold 24 hours after casting and left in the laboratory until the testing age. The impact viscosity coefficient of the panels was tested on the 28th day. The impact viscosity test was carried out with the help of a falling hammer according to ACI Committee 544; the impact resistant specimen was subjected to repeated strikes in one place. In this test, a hammer weighing 10 kg fell from a height of 600 mm on the panel.

### 2.2.5 Vapor permeability

The vapor permeability characteristics were determined according to ISO 12572. Three specimens of dimensions 200 × 100 × 70 mm were placed on glass trays inside which there was silica gel. The specimen was smeared with wax in 2 layers on the side faces (there was another layer of adhesive tape between the layers of wax). Thus, only the upper and the lower faces remained free. The mass of the flask was measured twice a day under normal conditions (23°C, 50% relative humidity). The coefficient of vapor permeability $\mu$ was calculated as the arithmetic average of the results of testing three specimens by Eq. (2):

$$\mu = \frac{Q_0 \delta}{F(P_1 - P_2) - Q_2 \mu_a}$$  (2)

where $Q$ is the stationary flow of water vapor (mg/m·h·Pa), $\delta$ is the specimen thickness (m), $F$ is the area of the sample surface to be passed (m²), $P_1$ is the partial pressure of water vapor above the specimen determined according to psychrometric tables based on the values of relative humidity and air temperature (Pa), $P_2$ is the average partial pressure of water vapor above the specimen (Pa), $\delta_a$ is the thickness of the air layer between the specimen and silica gel (m) and $\mu_a$ is the vapor permeability coefficient of air, equal to 0.135 mg/m·h·Pa.

### 2.2.6 Effective diffusion coefficient

Gas permeability was determined as an effective diffusion coefficient (taking into account the influence of the porous microstructure and humidity of concrete, compaction of the outer concrete layer with corrosion products) CO₂ in the layer of concrete composite subjected to carbonization on cubic specimens of dimension 100 × 100 × 100 mm. The test device (Fig. 9) has constant parameters of the gas environment: CO₂ concentration 10 ± 0.5% by volume, relative humidity 75 ± 3%, and temperature 20 ± 5°C. In total 12 specimens were tested. The specimens are kept in the chamber for at least 7 days and not more than the period during which the samples will be neutralized to 1/4 of their thickness.

The empirical data of the neutralized concrete layer thickness $X$ (in cm) were processed and the average value of this thickness was calculated using Eq. (3):

$$X = \frac{1}{n} \sum x_i$$  (3)

where $n = 12$ is the number of tests.

The reaction capacity of concrete is calculated by Eq. (4):

$$m_i = 0.4 \cdot CEM \cdot \rho \cdot f$$  (4)

where CEM is the cement content (g) per 1 cm³ of concrete, $\rho$ is the number of basic oxides in cement in terms of CaO in relative values by weight, taken according to the chemical analysis of cement (for an approximate calculation, $\rho = 0.6$) and $f$ is the degree of neutralization of concrete, being equal to the ratio of the number of basic oxides that have interacted with carbon dioxide to...
their total amount in cement (on average, \( f = 0.6 \)).

The effective diffusion coefficient for carbon dioxide \( D \) (cm\(^2\)/s) is calculated by the formula in Eq. (5):

\[
D = \frac{m_rX^2}{2C\tau}
\]

where \( C \) is the concentration of carbon dioxide in the chamber in relative values and \( \tau \) is the duration of exposure (s) to carbon dioxide on concrete.

### 3. Experimental results and discussion

Table 11 explains the effect of CB Fillers and Superplasticizer on slump flow, compressive strength, tensile strength, elastic modulus, dynamic compressive strength, impact viscosity coefficient, vapor permeability, and effective diffusion coefficient properties of FRSCC. The relations and interactions of variables on FRSCC performances were modelled by ANOVA method. In order to find the best fit including; linear, quadratic, and two-factor interaction model were evaluated to find the best valid models. The quality of models was controlled by \( R^2 \), which is a measure of how close the data are to the fitted regression line. Validation of the models was tested by probability of errors or P-value with 95% confidence level and statistical significant test at 5%.

| Sample number | Slump flow (mm) | Compressive strength (MPa) | Tensile strength (MPa) | Elastic modulus (GPa) | Dynamic compressive strength (MPa) | Impact viscosity coefficient (\( \mu \)) | Vapor permeability \([\text{mg/(m·h·Pa)}]\) | Effective diffusion coefficient (10\(^{-4}\) cm\(^2\)/s) |
|---------------|----------------|---------------------------|------------------------|-----------------------|-----------------------------------|----------------------------------------|-----------------------------------------|-------------------------------------------|
| 1             | 700            | 72.3                      | 14                     | 40.1                  | 99.2                              | 29                                     | 0.026                                   | 0.099                                    |
| 2             | 730            | 75.8                      | 15                     | 41                    | 100                               | 33                                     | 0.024                                   | 0.096                                    |
| 3             | 750            | 78.3                      | 15                     | 41.9                  | 102                               | 25                                     | 0.023                                   | 0.095                                    |
| 4             | 690            | 81                        | 16                     | 42.2                  | 108                               | 26                                     | 0.023                                   | 0.092                                    |
| 5             | 710            | 84.6                      | 17                     | 43.3                  | 119.1                             | 27                                     | 0.024                                   | 0.095                                    |
| 6             | 710            | 84                        | 16.8                   | 43                    | 117.1                             | 26                                     | 0.024                                   | 0.097                                    |
| 7             | 680            | 76                        | 15.2                   | 42.3                  | 100.1                             | 23                                     | 0.025                                   | 0.1                                      |
| 8             | 690            | 77.3                      | 15.4                   | 41.8                  | 100.9                             | 24                                     | 0.023                                   | 0.093                                    |
| 9             | 700            | 80.8                      | 16.1                   | 42                    | 102.2                             | 20                                     | 0.025                                   | 0.1                                      |

Table 12 shows the ANOVA results for eight different responses P-values less than 0.05 which indicate the model terms are weighty enough. In this study the A and B variables are the significant model terms. Values greater than 0.10 indicate the model terms are insignificant. If there are many insignificant model terms, model reduction may improve it. The models coefficients of determination \( R^2 \) have a reliable confidence with 0.89, 0.95, 0.94, 0.95, 0.91, 0.98, 0.94, and 0.98 of slump flow, compressive strength, dynamic compressive strength, tensile strength, elastic modulus, impact viscosity coefficient, vapor permeability, and effective diffusion coefficient, respectively, which are very close to 1.00. The predicted \( R^2 \) of models were in reasonable agreement with adjust \( R^2 \), whereas, the differences were less than 0.20 for all models.

Table 12 Analysis of regression models.

| Response                                    | Degree of freedom | \( R^2 \) | Adj-\( R^2 \) | Pre-\( R^2 \) | Adeq. Precision | F-Value | Model P-value |
|---------------------------------------------|-------------------|----------|--------------|---------------|-----------------|---------|---------------|
| Slump flow (mm)                             | 2.0               | 0.89     | 0.85         | 0.69          | 13.59           | 23.31   | 0.0015        |
| Compressive strength (MPa)                  | 3.0               | 0.95     | 0.92         | 0.85          | 16.62           | 33.59   | 0.0010        |
| Tensile strength (MPa)                      | 3.0               | 0.94     | 0.90         | 0.82          | 14.04           | 24.84   | 0.0020        |
| Elastic modulus (GPa)                       | 4.0               | 0.95     | 0.89         | 0.80          | 13.11           | 17.24   | 0.0087        |
| Dynamic compressive strength (MPa)          | 3.0               | 0.91     | 0.85         | 0.70          | 9.64            | 16.20   | 0.0052        |
| Impact viscosity coefficient (\( \mu \))   | 2.0               | 0.98     | 0.97         | 0.92          | 23.77           | 64.25   | 0.0007        |
| Vapor permeability \([\text{mg/(m·h·Pa)}]\) | 3.0               | 0.94     | 0.91         | 0.79          | 11.86           | 12.65   | 0.0015        |
| Effective diffusion coefficient (10\(^{-4}\) cm\(^2\)/s) | 3.0 | 0.98 | 0.96 | 0.92 | 24.21 | 83.33 | 0.0001 |
Fig. 10 Prediction efficiency of offered models
The coefficient estimation represents the expected change in response per unit change in factor value when all remaining factors are held constant. The intercept in an orthogonal design is the overall average response of all the runs. The coefficients are adjustments around that average based on the factor settings. **Table 13** demonstrates the details of generated models for different characteristics of FRSCC. The factor of probability is given to each variables to show the importance degree of variables on response performance. There are different statistically models which were used to fit variables on different responses including linear, quadratic, and 2 ways interaction models used for slump flow, compressive strength, tensile strength, elastic modulus, dynamic compressive strength, impact viscosity coefficient, vapor permeability, and effective diffusion coefficient, respectively.

### 3.1 Slump flow test of FRSCC

The effect of CB filler and SP on fresh FRSCC is shown in **Fig. 11**. The flow range was beginning from 670 mm in mix no. 7 when SP was in lower level (-1) and CB filler was in upper limit (+1) till to 750 mm when SP was in upper level (+1) and CB filler was in lower limit (-1). The results show the linear and direct effect of SP and CB filler on workability of fresh FRSCC. As it is understandable, the SP increases the flowability, however, as the ASCA available in CB demands high amount of water compared to the control mixture therefore the higher the amount of ASCA the more the water design and the higher the mean particle size the more the water consumption. The higher the amount of ASCA replacement requires a higher amount of super plasticizer and water content to maintain the suitable desired workability. Based on the results, no interaction among SP and CB filler was detected on workability of FRSCC.

### 3.2 Mechanical properties of FRSCC

#### 3.2.1 Compressive strength

The effects of CB filler and SP on 28 day compressive strength of FRSCC were revealed by counter graph and response surface in **Fig. 12**. Minimum 28 day compressive strength 72.3 MPa was obtained in mix no. 1 when both CB filler and SP were in lower levels and maximum 28 day compressive strength 84.6 MPa obtained when the both SP and CB filler were in their medium

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**Table 13** Variables coefficients estimated for models.

| Parameters                  | Estimate | A       | B       | AB      | A²      |
|-----------------------------|----------|---------|---------|---------|---------|
| Slump flow (mm)             | 3366.67  | 2016.67 | 1350.00 | -       | -       |
| Compressive strength (MPa)  | 124.83   | 9.88    | 31.74   | -       | 83.2050 |
| Tensile strength (MPa)      | 6.83     | 1.22    | 1.22    | -       | 4.4006  |
| Elastic modulus (GPa)       | 7.05     | 1.60    | 0.88    | 1.10    | 3.47    |
| Dynamic compressive strength (MPa) | 425.33 | 0.67    | 32.67   | -       | 392.00  |
| Impact viscosity coefficient (μi) | 74.83   | 66.67   | 8.17    | -       | -       |
| Vapor permeability [mg/(m·h·Pa)] | 0.023   | 0.0006  | -0.0001 | -       | 0.0016  |
| Effective diffusion coefficient (10⁻⁴ cm²/s) | 0.0933 | 0.0018  | 0.0010  | -       | 0.0045  |

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**Fig. 11** Contour plot and response.
levels. The results show the parabolic behaviour of CB filler as increasing the CB filler first increase the compressive strength, after crossing the optimum percentage of CB filler the compressive strength is dropping by increasing the CB filler. Based on the regression equation of parabola exposed in Table 13, it will be imaginable to detect the maximum percent of CB filler when the differential coefficient (y') of each function equals zero, the value of A represent the optimal CB filler amount to obtain the best compressive strength.

3.2.2 Tensile strength
The effect of SP and CB filler on tensile strength of FRSCC has been showed as response surface and contour line in Fig. 13. Like 28 day compressive strength, the tensile strength is showing the parabolic behavior of CB filler and increasing the SP gently increases the tensile strength of FRSCC as the min tensile happened when both SP and CB filler are at the lower limit (-1) and max tensile is on the mean level of both variables (0) with more than 21% improvement. No interaction between SP and CB filler was observed.

3.2.3 Elastic modulus
The effects of CB filler and SP on elastic modulus of FRSCC have been showed in Fig. 14. Based on measurements, the minimum modulus of elasticity 40.1 GPa happened at the lower limits (-1) of both CB filler and SP, and the maximum 43.3 GPa measured for the medium limits of both CB filler and SP (0). The result shows the linear behavior of SP and parabolic behavior of CB filler on modulus of elasticity. By increasing the SP percentage the modulus of elasticity of FRSCC has been improved. The interaction between CB filler and SP was observed.

3.2.4 Dynamic compressive strength
The dynamic compressive strength of FRSCC has been showed in Fig. 15. The result shows the positive effect of SP on dynamic compressive strength as increasing the SP increased the dynamic compressive strength. CB filler effect illustrated the parabolic treatment of it. First, adding CB filler raised the dynamic compressive strength; however, additional CB filler decreased the dynamic compressive strength performance.
The results clearly show the hydration of cementitious materials blended with CB filler play the main role in development of mechanical properties of FRSCC. One side the presence of ASCA stimulates the cement hydration (Le 2015). The moisture absorbed by the pore structure of the ASCA is released out of the pore to provide enough moisture for the surrounding. When the relative humidity of the matrix decreases during cement hydration, there will be an enhancement in the long time development of mechanical properties and reduce the amount of water to binder ratio over time (Van Tuan et al. 2011). Bui et al. (2005) conducted a study which indicated that concrete containing rice husk ash as replacement of cementitious materials at lower water to cement ratio have better performance when compared to the control concrete. On the other side, the quartz powder can be used as filler which improves the microstructure of concrete matrix (Zhang et al. 1996; Mosaberpanah et al. 2019). Thereby, by reducing the initial porosity of the mixture final strength will be improved. The formation of C-S-H (calcium silicate hydrate) is not the only viable parameter for the strength development of cement blended with ASCA because of its mesoporous structure which absorbs high amount of water and allows the diffusion of Ca^{2+} ions into the internal pore structure to enhance the hydration rate of cementitious materials and improve the pozzolanic reaction (Rößler 2014a, 2014b), however, as the modellings show adding more CB filler will reduce the hydration rate and cause to reduce the concrete performance. As Alsadey (2012) explained adding SP will provide more water for concrete mixture, not only the hydration process will not be concerned, but also, it will accelerate the defloculating of cement particles with additional water. Henceforth, increasing in the SP dosage will increase the entrapped water and promote hydration of cement. However, increment in dosage of admixture will enhance the mechanical properties of concrete.

3.2.5 Impact viscosity coefficient

The effect of the fiber bridge determines the absorption of the impact energy after the onset of cracking and, therefore, the impact plasticity of the concrete. The impact viscosity coefficient $\mu$, expressed as the ratio be-
between the final and initial impact energies and shown in Fig. 16 is a good indicator of the plasticity of concrete subjected to shock loading.

The initial impact energy is proportional to the number of impacts before the formation of the first crack, and the final impact energy is proportional to the number of impacts before failure. Thus, the impact viscosity coefficient was calculated as the ratio of the number of impacts to fracture to the number of impacts before the formation of the first crack. Obviously, the final impact energy (before failure) is significantly higher than the energy spent on the appearance of the first crack. Even after the formation of the first cracks, the sample was able to withstand a large amount of shock load before it collapsed. The final impact energy (before failure) exceeded the published results for high strength concrete (Fediuk et al. 2018a; Ibragimov et al. 2019; Arya 2018). This means that the developed fiber reinforced concrete has high impact strength and excellent potential for use as a structural material for protective structures.

3.3 Vapor permeability

Figure 17 shows the effect of CB filler and SP on vapor permeability of FRSCC. The result shows a negative effect of SP and a parabolic effect of CB filler on vapor permeability of FRSCC. Increasing the CB filler first reduced the vapor permeability and then after crossing the minimum, additional CB filler increased the vapor permeability. As Van Tuan et al. (2011) mentioned a pozzolanic reaction and filler effect of RHA exist in CB filler improved the porosity of the samples and therefore the permeability was reduced. For cement based material like concrete, C-S-H is the most important product through the hydration process and it is mainly responsible for the strength of concrete matrix. RHA is basically high active pozzolanic material due to existing high value of silicate and adding of such material into the cement paste will reduce calcium leaching as they react with calcium hydroxide (CH) and form additional C-S-H gel and also improve the microstructure of the paste which is derived to increase the strength of hardened cement paste. Limestone consists mainly of CaCO₃ with some clay content and organic matter. Limestone is not
a pozzolan; therefore, it creates no C-S-H during hydration (Hou et al. 2015; Thomas 2018; Chopra and Siddique 2015; Van 2013). However, limestone particles that have a nominal diameter of less than 0.1 mm promote hydration by providing nucleation sites for the reaction products which improves the microstructure of FRSCC.

4. Conclusions

Many researchers have used either limestone powder or quartz powder as secondary raw material in fiber reinforced self-consolidating concrete matrix without studying their mutual blends. In this study, the influence of waste CB filler including the composition of active silica containing additive (74%), quartz sand (13%) and limestone crushing waste (13%) which were substituted with 30%, 35% and 40% of total composite binder and different ratio of superplasticizer were studied on fresh, rheological, mechanical, dynamical and durability including slump flow, compressive strength, tensile strength, elastic modulus, dynamic compressive strength, impact viscosity coefficient, vapor permeability, and effective diffusion coefficient properties of Fiber Reinforced Self Compacting Concrete using response surface methodology. The models coefficient of determination R² with reliable confidence of 0.89, 0.95, 0.94, 0.95, 0.91, 0.98, 0.94, and 0.98 of slump flow, compressive strength, tensile strength, elastic modulus, dynamic compressive strength, impact viscosity coefficient, vapor permeability, and effective diffusion coefficient, respectively were simulated and verified in two modelling types. Linear modelling was implemented for slump flow and impact viscosity coefficient tests and the quadratic model was fitted for the rest responses.

Replacement of cement by waste CB as a supplementary cementitious material has a positive effect on mechanical properties of FRSCC from 30% to around 35% of cement replacement as rice husk ash is a pozzolanic additive, it started to show pozzolanic reactivity after curing. In addition, ASCA, Quartz, and waste limestone reduced the pore structure significantly in the specimens and lowered permeability and it also increased durability. It was also observed that the specimens containing more than 35% waste CB start to decrease the mechanical properties of FRSCC. Adding the superplasticizer improved the performance of FRSCC in all aspects in the given range. Increasing the waste CB decreased the vapor permeability and effective diffusion coefficient of FRSCC by improving the hydration rate and decreasing the pores of the concrete matrix.

Designed FRSCC has the potential to be used as a material for protective structures, because it is able to provide comprehensive protection against the dynamic effects and penetration of gases.

It is advisable to continue research in the direction of expanding the range of building composites to create a safe human environment through the development of multicomponent composite binders that allow controlling the structure formation processes at the nano, micro, and macro levels. This will create new composites for widespread use, both in civil engineering, and for the construction of special objects.

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List of notations

- $E_i$: impact energy (J)
- $m$: hammer weight (10 kg)
- $N$: number of hammer blows
- $N_f$: number of hammer blows causing failure
- $N_c$: number of hammer blows causing the first crack
- $\mu$: impact viscosity coefficient
- $\mu$: coefficient of vapor permeability
- $Q$: stationary flow of water vapor (mg/m^2·h·Pa)
- $\delta$: specimen thickness for vapour permeability test (m)
- $F$: area of the sample surface for vapor passed (m^2)
- $P_1$: partial pressure of water vapor above the specimen determined according to psychrometric tables based on the values of relative humidity and air temperature (Pa)
- $P_2$: average partial pressure of water vapor above the specimen (Pa)
- $\delta_a$: thickness of the air layer between the specimen and silica gel (m)
- $\mu_a$: vapor permeability coefficient of air
- $X$: neutralized concrete layer thickness (cm)
reaction capacity of concrete

cement content (g) per 1 cm³ of concrete

number of basic oxides in cement in terms of CaO in relative values by weight

degree of neutralization of concrete

effective diffusion coefficient for carbon dioxide

concentration of carbon dioxide in the chamber in relative values

duration of exposure to carbon dioxide on concrete (s).