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Article

Effect of Styrene–Butadiene Rubber Latex Dosage on the Workability and Compressive Strength of Concrete Incorporating Manufactured Sand as Fine Aggregate

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Abstract: The scarcity of natural river sand has encouraged interest in the use of manufactured sand (M-sand) as a fine aggregate in structural concrete. Additionally, the addition of polymers to the concrete mix can improve the engineering properties of the resultant concrete. M20 grade concrete is prepared using M-sand as the fine aggregate and styrene-butadiene rubber (SBR) latex at replacement levels of 2%, 4%, 6% and 8% of the mass of the cement. The mix is designed according to Indian Standard methods with a water-cement ratio of 0.50 and a cement content of 394 kg/m³. The slump of the mix increases from 85 mm for the control mix to a maximum of 110 mm for 6% SBR latex content before decreasing to 95 mm for 8% latex replacement. The 28-day compressive strength of concrete with 6% SBR latex replacement has the highest strength values (21.14 MPa at 7 days and 27.03 MPa at 28 days) while the 8% replacement level gives the lowest strength (18.74 MPa at 7 days and 25.28 MPa at 28 days). All the tested concrete had a 28 day compressive strength greater than the 20 MPa characteristic strength required for M20 grade concrete. These results show that 6% SBR latex replacement in M20 grade concrete with M-sand as fine aggregate gives the highest strength and hence can be considered the optimum dosage of polymer in this type of concrete. A framework for using machine learning to model the properties of such concrete is proposed.
Keywords: manufactured sand; styrene–butadiene rubber latex; polymer-modified concrete; workability; compressive strength; mix design; M20 concrete.

1. Introduction

Due to its versatility, mouldability and low cost, concrete is the most widely used construction material in the world. However, the performance of concrete depends upon the quality of its constituents. As the extraction of natural river sand is unsustainable due to environmental issues, manufactured sand (M-sand) which is produced by crushing hard granite rock is used as the replacement for natural sand. M-sand exhibits properties such as grading, absence of organic impurities, silt and clay coatings, and the interlocking of the particles with the cement paste that give it properties similar to natural sand concrete.

Another way of improving concrete is through the use of polymers. Polymers have been used in concrete since ancient times to enhance their tensile and flexural strength, impermeability and chemical resistance properties. There are two different technologies used for incorporating polymers into concrete. In polymer-impregnated concrete, the hardened and dried concrete are infiltrated through vacuum or pressured with monomer liquids that subsequently polymerize. In polymer-modified concrete also known as latex-modified concrete, latex dispersions are mixed into fresh concrete at the mixing stage. Styrene-butadiene rubber (SBR) is one of the most common latex modifiers that have been used to increase the flexural strength, tensile bond, anti-penetrability and frost resistance of mortars and concrete. This study falls into the category of polymer-modified concrete because the SBR latex was added to the concrete during the mixing stage.

Although concrete using both M-sand and SBR have been individually studied, few studies have investigated the combined use of both constituents in normal concrete strength. Moreover, the dosage of SBR latex that should be used in concrete that use M-sand as its fine aggregate is not well established. Since SBR additives exhibit plasticizing, air entraining and polymer-modifying effects upon normal concrete, their effect on the compressive strength of concrete is dose dependent. Thus, the main objectives of this investigation were to:

(i) proportion an M20 grade concrete using M-sand as the complete fine aggregate constituent;

(ii) determine the workability of the fresh concrete prepared with 2%, 4%, 6%, and 8% SBR latex by mass of cement;

(iii) determine the 7- and 28-day cube compressive strength of the concrete prepared with the SBR latex at the aforementioned dosages;

(iv) determine the SBR latex dosage that provides the best workability and strength for the M-sand concrete within the range of dosages tested.

Literature Review

Due to the depletion of natural river sand and environmental restrictions on sand extraction, manufactured sand (M-sand), which is produced by crushing rock deposits, has emerged as a mainstream alternative fine aggregate in construction [8], [10]. However, M-sand has angular particles with high microfines and rough texture that make it have a higher demand for water than natural sand [8], [9]. Styrene-butadiene rubber (SBR) latex is the most common polymer used to modify cement-based materials. The dosage of SBR latex in cement is commonly between 0% and 20% of the weight of the cement, and it can alter the properties of both fresh and hardened cement [1], [2]. Furthermore, since SBR latex acts as a plasticizing, air-entraining, and film-forming agent, dosage variations have effects on both the workability and strength of concrete [1]. A review of the literature regarding these individual topics will help to justify the need for combined studies on the topic of SBR latex in M-sand concretes.

Effect of SBR Latex Dosage on Workability

The addition of SBR latex to concretes increases the workability of fresh concrete [1], [2]. The surfactants in the latex reduce the charge between the cement particles, and the spherical latex particles contribute to a "ball-bearing" effect between the particles that improves workability [1], [2]. Additionally, air entrained by SBR latex also increases the workability of fresh concretes. Studies have shown that increasing the dosage of SBR latex to concrete increases the slump of fresh concrete [4]. For concretes that use SBR latex as a replacement for up to 15% of the cement by weight, workability increases linearly with the dosage of latex [4]. For mortars with 15% SBR latex by weight of cement, fluidity increases to 37-40% compared to controls with the same ingredients but without SBR latex, along with a reduction of the yield stress and plastic viscosity of the mortar [2]. Furthermore, freshly mixed concrete with SBR latex exhibit excellent workability characteristics. The workability of the fresh concretes can be enhanced enough to allow their use as 3D printable materials [2], [13]. In some cases, however, latex dosage must be reduced in cement-rich concretes to avoid increasing the workability beyond the target specification for the construction project [4]. Consequently, the addition of SBR latex can improve the workability of concrete with high water demand, such as M-sand concrete [1], [4].

Effect of SBR Latex Dosage on Compressive Strength

The dosage of SBR latex has been shown to have both positive and negative effects on the compressive strength of concrete, and those effects are dependent upon the age of the concrete, the dosage of SBR latex, the type of concrete, and the dosage of other ingredients common to concrete [4], [5]. Studies into concrete made with natural sand have shown that SBR latex dosage has a retarding effect on the initial (around 7 days) compressive strength of the concrete [4], [5]. XRD and FTIR analyses of concretes containing SBR latex have revealed that the SBR latex delays the initial hydration of the cement but ultimately promotes the formation of more C-S-H gel, which enhances the strength of concretes at later ages [3]. However, at 28 days of age, the addition of SBR latex has increased the strength of concretes; concretes with 15% SBR latex have gained 21% of the strength of concretes without SBR latex by weight of cement [2]. Additionally, high strength concretes with strength values of 50 and 60 MPa have shown increases in strength of up to 20% when 10% SBR latex was added by weight of cement [2]. Other studies, however, have reported a monotonic decrease in the compressive strength of concretes with increasing dosage of SBR latex [5], [7], [12]. For concretes containing 5% to 15% of SBR latex replacement by weight of cement, the compressive strength and elastic modulus of the concretes decreased as the dosage of SBR latex increased [12]. Additionally, studies on other types of concretes, such as lightweight-aggregate concretes, have indicated the presence of a penalty in the compressive strength of the concretes due to the addition of SBR latex [7]. These opposing effects are due to the fact that SBR latex both improves the strength of concretes by forming films that fill in microcracks that form during hydration [1], [3], and that it can reduce the strength of concretes by air entraining into the concrete, retarding the cement hydration, and the stiffness of the latex phase within the cement matrix [2], [5], [7]. Consequently, SBR latex dosage between 5% and 10% has been found to increase the strength of concrete, while dosages that are beyond 15% are often found to be counterproductive to increasing the strength of concretes [1], [2], [5].

Manufactured Sand as Fine Aggregate

When M-sand is used as the sole fine aggregate in concrete, the water-to-cement ratio must be increased to provide the workability that is common to concretes with natural sand as the fine aggregate [8]. However, if M-sand is used as the sole fine aggregate in the same water-to-cement ratio as natural sand concretes, the compressive and flexural strengths of M-sand concretes are higher [8]. Concrete with M-sand exhibit strength gains of between 7% and 33% and workability losses of between 11% and 67% compared to concretes with natural sand [14]. For self-compacting concretes, which require high workability, M-sand concretes require adjustments to the dosage of superplasticizers to compensate for the reduction in workability of M-sand concretes [9]. Studies have shown that the content of stone-powder in M-sand and the gradation of M-sand can impact the workability of M-sand concretes and its 28-day compressive strength [10]. Additionally, studies that used machine learning algorithms to determine optimal dosages of M-sand replacements found that M-sand concretes can have 28-day compressive strengths that are the same or greater than concretes that use natural sand [11].

Intersection: SBR Latex in M-Sand Concrete and the Research Gap

M-sand concretes have lower workability but higher compressive strength than concretes with natural sand [8], [9]. The addition of SBR latex improves the workability but can reduce the 28-day compressive strength at high dosages [2], [5], [7]. As such, a dosage of SBR latex of around 5% to 10% by weight of cement can provide the workability required from M-sand but not detrimentally impact the strength of the M-sand concretes [1], [2], [8]. SBR latex has been shown to successfully address the problems of weak interfaces of concrete with recycled sands or lightweight aggregate [3], [7]. Additionally, it has improved the workability of fibre-concretes with high workability requirements [6]. However, there are few studies on concretes with 100% M-sand as the fine aggregate with SBR latex [9], [10], [11]. Most of the studies on SBR latex use natural sand or silica sand [2], [5], [13], and the majority of the studies on M-sand use chemical admixtures rather than SBR latex [9], [10], [11]. Consequently, there are research gaps regarding the interactions between M-sand and SBR latex, such as the effect of the stone-powder content in M-sand on the dosage of SBR latex required, the interaction between air entrained by SBR latex and the microfines in M-sand, and the effect of SBR latex dosage on the 28-day strength of M-sand concretes with crushed M-sand aggregate.

The dosage of SBR latex has a positive and detrimental effect on the workability and compressive strength of concrete, respectively [2], [5], [7]. The benefit of SBR latex for workability is monotonically increasing with dosage, whereas the benefit to compressive strength is unimodal with an optimal dosage between around 5% and 10% of the weight of the cement [1], [2], [5]. The use of M-sand in concretes is associated with reduced workability and increased strength [8], [9]. Consequently, an optimum dosage of SBR latex for M-sand concretes is an interesting area of study and a potential research gap in the existing literature on concretes with M-sand aggregates and SBR latex.

2. Materials

2.1 Cement

Ordinary Portland Cement of 53 grade with a specific gravity of 3.15 was used throughout the investigation.

2.2 Manufactured sand (fine aggregate)

The M-sand produced by crushing hard granite and having a maximum particle size of below 4.75 mm was used as the fine aggregate. The crushed granite particles are cubical with ground edges and are washed and graded prior to use. Table 1 presents the physical properties of the M-sand used in the experiment. Typical literature values for these properties are also given in parentheses for ease of reference. The appearance of the M-sand is as shown in Fig. 1.

The specific gravity of the sand was found to be 2.56 (Table 1). This value is different from the value of 2.62 that was used in the mix design calculations of Section 3. As the amount of each of the ingredients of the concrete mix that was batched is given in Table 2, this discrepancy has no impact on the actual quantities of the ingredients that were used in the experiment. However, the test should be performed again prior to any future attempts to re-proportion the ingredients.

Fig. 1. Manufactured sand (M-sand) used in the study.

Table 1. Physical properties of M-sand (values as measured; typical ranges in parentheses).

S. No.	Property	Value
1	Specific gravity	2.56
2	Water absorption (%)	0.14%
3	Fineness modulus	2.52
4	Bulk density (kg/m³)	1573.33 kg/m³

2.3 Coarse aggregate

Crushed angular coarse aggregate of nominal maximum size 20 mm was employed. The specific gravity of the aggregate was 2.74 with a water absorption of 0.5% and a free surface moisture content of nil for both the coarse and fine aggregates used in the concrete.

2.4 SBR latex

The styrene-butadiene latex was added to the concrete at the mixing stage at dosage levels of 2%, 4%, 6% and 8% of the mass of cement used. This corresponds to 7.88, 15.76, 23.64 and 31.52 kg of latex per 1000 kg of cement for each dosage respectively.

3. Mix proportioning

The concrete was proportioned for grade M20 following the procedure of IS 10262 read with IS 456, using the material properties of Section 2.

3.1 Target mean strength

The target mean compressive strength at 28 days is obtained from:

$$f'ck = fck + 1.65\ S$$

where f'ck is the target mean compressive strength at 28 days (MPa), fck is the characteristic compressive strength at 28 days (20 MPa for M20), and S is the standard deviation, taken as 4 MPa for M20 grade in the absence of site data. Hence f'ck = 20 + 1.65 × 4 = 26.6 MPa.

3.2 Water–cement ratio and water content

For the M20 grade, as per IS 10262, the water-cement ratio is 0.50. For 20 mm size of aggregate, the water content is 186 litres per m³ for a slump of 25 to 50 mm. For a target slump of 100 mm, the content is increased by 3% for every 25 mm increase in slump. Therefore, the water content is 186× (1 + 0.03×100/25) = 200 litres per m³.

$$w = 186 \times (1 + 0.06) = 200\ L/m^3$$

3.3 Cement content

$$c = w / (w/c) = 197 / 0.50 = 396\ kg/m^3$$

This lies between the stipulated minimum of 320 kg/m³ and maximum of 450 kg/m³.

3.4 Aggregate proportions

where the variables are defined above. Thus, c = 197 / 0.50 = 396 kg of cement per m³ of concrete. This value is within the range of 320 to 450 kg of cement per m³ of concrete as per IS 10262 specifications.

3.4 Aggregate proportions

For 20 mm size of aggregate with fine aggregate having a fineness modulus of around 2.4, the coarse aggregate should occupy 62% of the total volume of the aggregates. However, since a higher degree of workability is required, the volume fraction is decreased by 10%. Thus, the volume fraction of coarse aggregate is 0.62×0.90 = 0.56 and the fine aggregate is the remainder; 0.44 by volume of the total aggregate in the concrete.

3.5 Absolute-volume calculation and batch quantities

The volume of cement used in the mix is 394 / 3.15 / 1000 = 0.125 m³ of cement. The volume of water is 0.197 m³. These volumes in addition to the volume of latex used are subtracted from the total volume. The remainder is distributed between the coarse aggregate and M-sand in the volume ratio of 0.56:0.44 as per their individual specific gravities. The mass of each of the aggregates is calculated from the following relation:

$$M = e \times v \times G \times 1000$$

where M is the aggregate mass (kg/m³), e is the residual aggregate absolute volume (m³), v is the volume fraction of the aggregate concerned (0.56 for coarse aggregate and 0.44 for M-sand) and G is its specific gravity. The values of the residual aggregate volume employed for the 2%, 4%, 6% and 8% SBR mixes were 0.67, 0.66, 0.65 and 0.64 m³ respectively. The batch quantities resulting from these calculations are shown in Table 2.

Table 2. Mix proportions per cubic metre of concrete (as batched).

Mix (SBR %)	Cement (kg/m³)	W (kg/m³)	M-sand (kg/m³)	CA (kg/m³)	SBR latex (kg/m³)	w/c
2%	396	200	778	1028	7.88	0.50
4%	396	200	766	1012	15.76	0.50

6%	396	200	740	997	23.64	0.50
8%	396	200	730	982	31.52	0.50

4. Experimental methods

4.1 Mixing

Thorough mixing is essential for a homogeneous mass of uniform colour and consistency. Machine mixing with a tilting-type power-operated mixer was adopted, and approximately 10% of additional material was batched to allow for mixing losses (Fig. 2).

Fig. 2. mixing of fresh concrete.

4.2 Compaction

Compaction expels the air entrapped in fresh concrete. The lower the workability of the concrete mix, the more air is entrapped. Hand compaction was achieved using a tamping rod to compact the fresh concrete in layers placed into the moulds (Fig. 3).

Fig. 3. Compaction of concrete specimens.

4.3 Curing

The specimens were left in their moulds 24 hours after casting. After the moulds were removed from the specimens, the specimens were placed into a curing tank at approximately 30 °C and 90% relative humidity until testing at 7 and 28 days (Fig. 4).

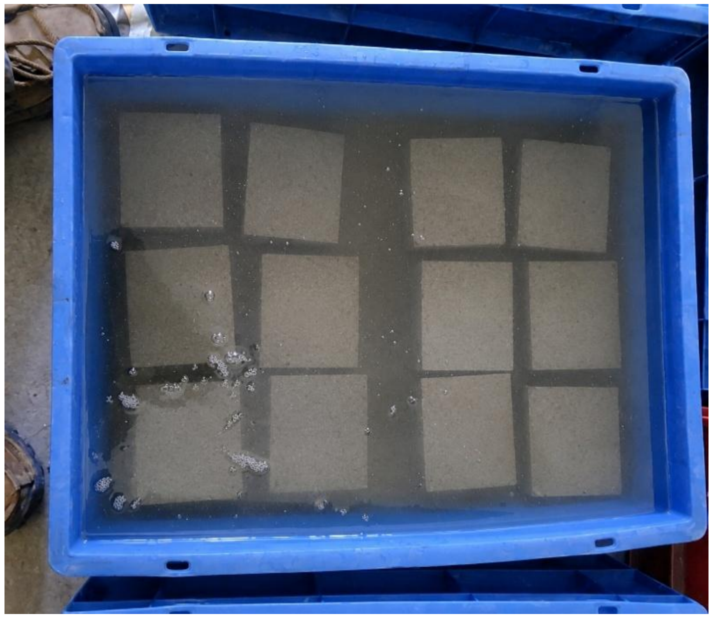

Fig. 4. Water curing of cube specimens.

4.4 Workability (slump) test

The slump test is performed to determine the consistency of the freshly mixed concrete, and to provide some indication of the consistency of the batches of concrete. The internal surface of the mould is cleaned of any superfluous moisture, and the mould is filled in four layers, each of which is approximately one quarter of the height of the mould. Each layer of concrete is compacted 25 times with the tamping rod, distributing the compactions evenly over the cross-section of the mould; the mould is then removed from the mixer, raising it slowly and vertically until the slump test is performed (Fig. 5).

Fig. 5. Slump-cone test on fresh concrete.

4.5 Compressive-strength testing

Specimens of 150 mm × 150 mm × 150 mm were tested in a compression testing machine to determine the load that the concrete can withstand at 7 and 28 days of curing (Figs. 6 and 7). Testing the concrete specimens is an inseparable part of the quality programme of the concrete industry to guarantee the performance of the concrete in terms of strength and durability.

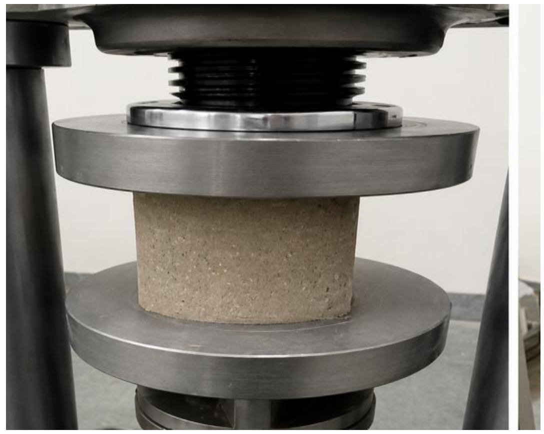

Fig. 6. Compression testing machine with cube specimen.

Fig. 7. Cube specimen at failure under compression.

5. Results and discussion

5.1 Workability

Table 3 and Fig. 8 show the slump values as they are measured. The slump value increases with the dosage of SBR from 85 mm at 2% to a maximum of 110 mm at 6% before decreasing to 95 mm at 8%. The initial decrease in slump is due to the plasticising action of the latex which acts in a similar way to ball bearings to reduce the friction between the particles of the mix, as well as the air that is entrained by the latex particles. The reduction in slump at 8% is due to the increasing cohesiveness of the paste with increasing dosage of the polymer.

Table 3. Slump values (as measured).

Polymer (%)	Slump value (mm)
2	85
4	90
6	110
8	95

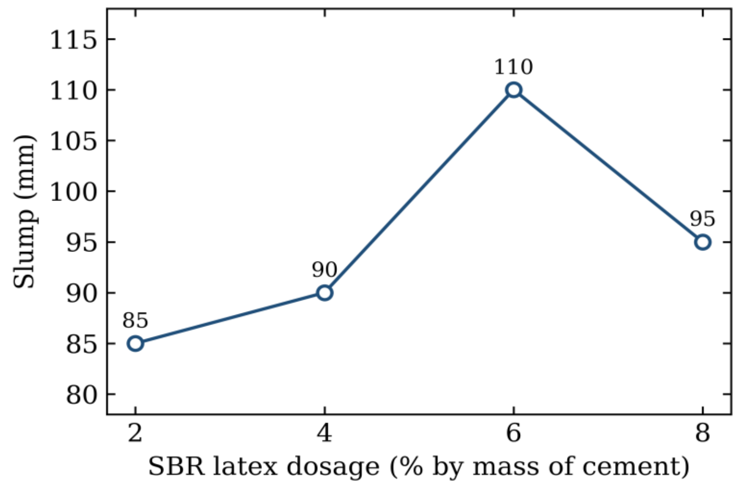

Fig. 8. Variation of slump with SBR latex dosage.

5.2 Compressive strength

The 7- and 28-day cube compressive strengths are reproduced unchanged in Table 4 and shown in Figs. 9 and 10. Each tabulated value is the reported result for the corresponding mix and age; replicate counts and standard deviations were not recorded.

Table 4. Compressive-strength test results (as measured).

S. No.	Cement (kg/m³)	M-sand (kg/m³)	Polymer (%)	7 days (MPa)	28 days (MPa)
1	396	778	2%	20.05	26.15
2	396	766	4%	19.83	26.37
3	396	740	6%	21.14	27.03
4	396	730	8%	18.74	25.28

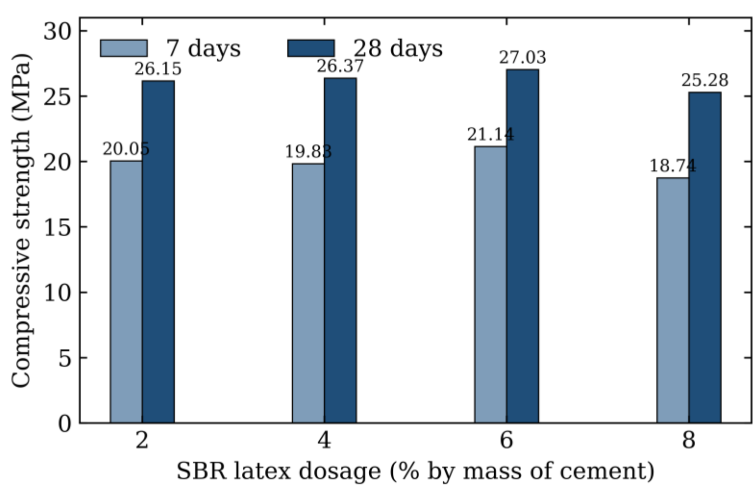

Fig. 9. Compressive strength at 7 and 28 days for each SBR dosage.

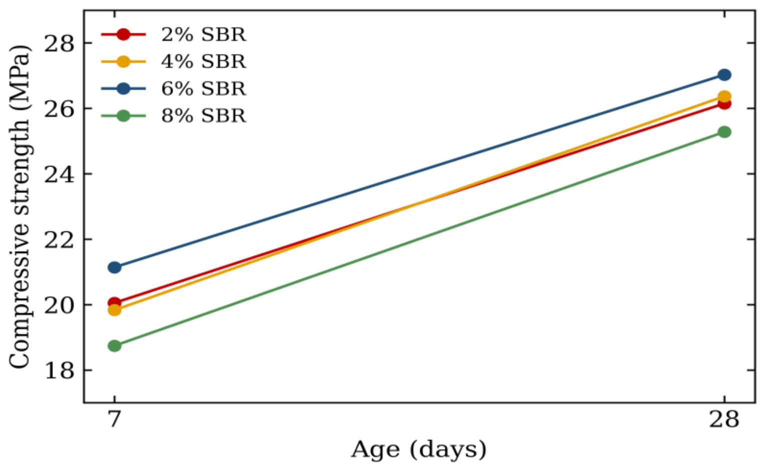

Fig. 10. Strength development between 7 and 28 days for each mix.

Three observations follow directly from the data. First, all of the mixes have exceeded the characteristic strength of 20 MPa at 28 days, indicating that it is possible to produce M20 grade concrete using M-sand as the complete fine aggregate. Second, the 6% SBR dosage has produced concrete of the highest strength, with strengths of 21.14 MPa at 7 days and 27.03 MPa at 28 days and was the only concrete mix to reach the target mean strength of 26.6 MPa at 28 days. Third, the relationship between the dosage of SBR powder and the 28-day strength of the resulting concrete is not monotonic; relative to the 2% SBR powder dosage, the 28-day strength of concrete containing 4% and 6% SBR powder by mass had increased by 0.84% and 3.37% of the 2% SBR powder strength, respectively, but the strength of concrete containing 8% SBR powder had decreased by 3.33% of that of the 2% SBR powder strength (Fig. 11).

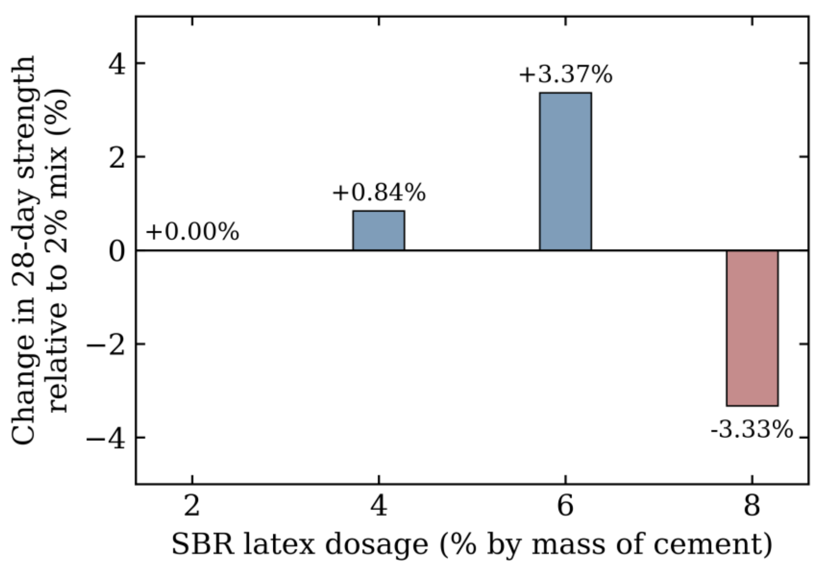

Fig. 11. Change in 28-day compressive strength relative to the 2% SBR mix (within-series comparison).

5.3 Mechanistic interpretation

The proximity of the optimum value to the 6% SBR value is in accordance with the accepted picture of latex modification of cement pastes. At low and moderate dosages, the latex particles coalesce to form films which fill the pores of M-sand particles and cracks in the cement matrix, thereby enhancing the strength of the composite material. However, at higher dosages the surfactants present in the latex introduce more air into the fresh mortar mix and latex particles soften the matrix, leading to a reduction in compressive strength of the mortar. Both these factors, therefore, may explain the reduction in compressive strength at 8% SBR. Although the proposed explanation for the increase in strength at 6% SBR is reasonable, it requires confirmation through analyses of the air voids content and microstructure of the samples, neither of which were undertaken in this study; hence, no claims can be made regarding the microstructure of the mortar samples.

The 7-day strengths of all mixes decreased to between 74 and 78% of their 28-day strengths, which is within the range expected of OPC 53 concrete. This indicates that the SBR latex had little effect on the hydration of the cement particles. Based on the above discussions, it can be stated that 6% SBR by mass of cement is the preferred dosage for use in M20 M-sand concrete.

6. Machine Learning Model Development: framework, architecture and validation protocol

Data-driven models are increasingly used in construction-materials research to map mixture and process variables to mechanical properties, complementing mechanistic understanding with quantitative prediction. Machine learning models have been used in the study of construction materials to relate the properties of the materials to various variables. The following section provides a complete description of the machine learning programme that will be used to analyse the SBR-modified M-sand concrete system. The experimental dataset that has been used consists of four mixture points and one strength value for each mixture point. Furthermore, there are no replicates of any of the mixtures that have been tested. Consequently, any measure of the performance of the machine learning models on this dataset would be meaningless. Thus, no machine learning model has been trained on this dataset, and there are no reported statistics of the performance of any model on the data provided. The remainder of this section describes the complete protocol that will be followed in applying machine learning models to the system once the database of specimens has been established as described in Section 6.3.

6.1 Candidate models and rationale

Table 4 shows four model families. The artificial neural network (ANN) can approximate any continuous function, making it ideally suited to the non-monotonic relationship between SBR dosage and strength; random forests (RF) are robust to outliers and do not require scaling of input features; extreme gradient boosting (XGBoost) is one of the best models for tabular data of similar sizes to this dataset; and support-vector regression using a radial-basis-function kernel (SVR-RBF) often achieves high accuracy with small sample sizes. By including two models of each of the two main types, any conclusions from the study will not be based on a single model family.

6.2 Input features and output targets

Table 5 defines the various features and the target variables to be modelled. Since the water-cement ratio and its components are influential on the strength of concrete, they are included in the model despite the availability of other potential features. Similarly, as SBR is the variable of interest in this study, its dosage is included as a feature. The amounts of cement and sand and the fineness modulus of sand are included as they are properties of the M-sand used in this study. Age is another feature as concrete of different ages may attain different strengths; although individual variables of 7 days and 28 days are modelled separately, they can be combined into a single feature in the model. Slump can also be used as an additional target variable alongside the features, or as an additional input to the model for the target variable. Finally, the target variables are the strength of the concrete samples, either in terms of split-tensile strength or water absorption; split-tensile strength and water absorption can be used as additional target variables for the model once they are measured.

Table 5. Input features and output targets with engineering rationale.

Variable	Unit	Engineering significance
Cement content	kg/m^3	Binder availability; hydrate volume
Water content	kg/m^3	Workability and capillary porosity
Water–cement ratio	–	Dominant strength driver (Abrams)
M-sand content	kg/m^3	Fine-aggregate packing; paste demand of angular particles
Coarse-aggregate content	kg/m^3	Skeleton stiffness; ITZ area

SBR dosage	% of cement	Treatment variable; film formation vs air entrainment
Fineness modulus (fine agg.)	–	Grading coarseness; water demand
Age	days	Hydration maturity
Slump (input or aux. target)	mm	Fresh-state proxy for dispersion and air content
Compressive strength (target)	MPa	Primary structural property

6.3 Database requirements and preprocessing

In order to provide adequate power to the statistical analyses, a minimum of approximately 100 specimen-level data records will be used. Such data will be obtained from both the expanded in-house programme with every individual cube value that is recorded, as well as from literature datasets on SBR-modified and M-sand concrete. Each record will be explicitly cited to enable the analysis of potential effects of each laboratory from which the data originated. Prior to statistical analysis, the datasets will be preprocessed in a fixed and defined series of steps. First, all units will be converted to SI units; any records that appear to contain physically impossible values will be removed; any records that are missing values will be removed if they are missing the target variable, but will either be removed or imputed to the median of the remaining records for the same dataset if they are missing only one of the input variables; any records that have values outside of the interquartile range will be flagged (but not deleted) for inspection; and finally, the continuous variables will be scaled to between 0 and 1 for the ANN, standardized to have a unit variance for the SVR, no scaling will be performed for the tree ensembles, and all scaling will be performed only upon the training folds of the respective models. Finally, the models will be partitioned into training and testing sets according to SBR dosage levels.

6.4 ANN architecture and training

The ANN is a fully connected feed-forward network (Fig. 12) mapping the normalised feature vector x to predict strength through successive transformations of the form:

$$h(l) = \varphi(\ W(l)\ h(l-1) + b(l)\ ),\quad \hat{y} = W(out)\ h(L) + b(out)$$

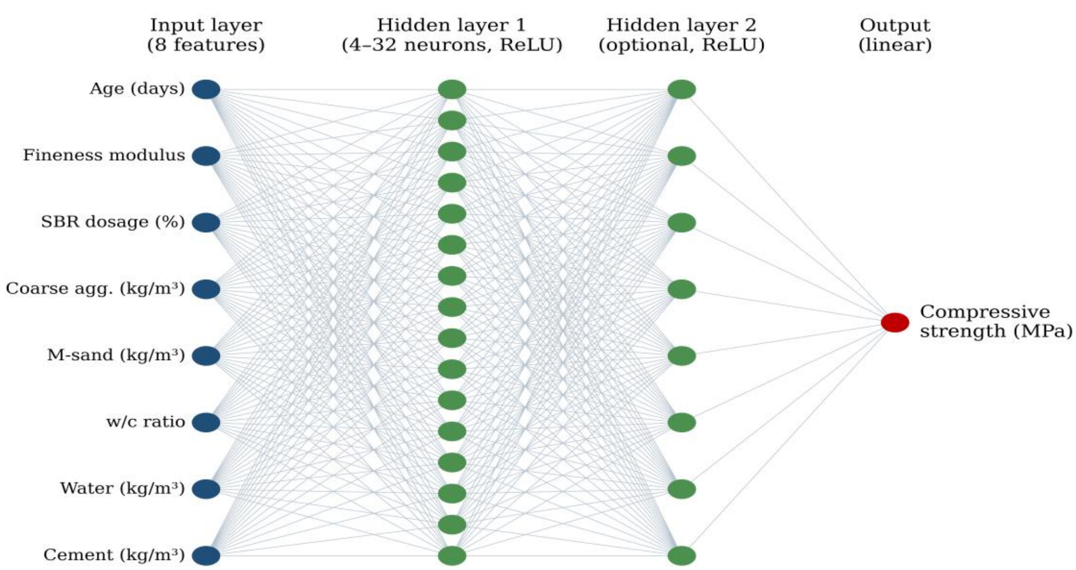

Fig. 12. Architecture of the proposed feed-forward ANN (schematic; neuron counts subject to grid search).

6.5 Validation protocol and evaluation metrics

Model assessment will employ five-fold cross-validation with repetition over at least ten random seeds for each model. Nested cross-validation will be used to select the model's hyperparameters such that performance is unbiased by this model tuning process. Each of the four models will be evaluated on the same cross-validation folds. Each model's performance will be assessed using the coefficient of determination, root-mean-square error, mean absolute error and mean absolute percentage error:

$$R^2 = 1 - \Sigma(y_i - \hat{y}_i)^2 / \Sigma(y_i - \bar{y})^2$$

$$RMSE = \sqrt{[\ (1/n)\ \Sigma(y_i - \hat{y}_i)^2\ ]}$$

$$MAE = (1/n)\ \Sigma|y_i - \hat{y}_i|$$

$$MAPE = (100/n)\ \Sigma|(y_i - \hat{y}_i)/y_i|$$

where y_i and $\hat{y}_i$ are the measured and predicted strengths of record i, $\bar{y}$ is the mean of all measured strengths and n is the total number of records within that fold. Each of these metrics will be reported as the mean ± standard deviation across all folds and seeds never from a single split of the database. For each of these tables, a statistical test will be performed to determine whether the differences between the models are significant; the corrected paired t-test or the Wilcoxon signed rank test will be used at a significance level of $\alpha = 0.05$. The complete experiment is summarised in Fig. 13.

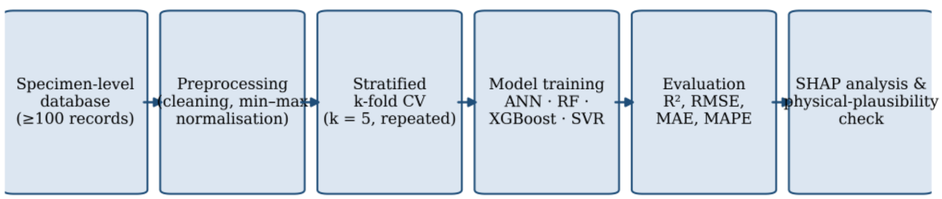

Fig. 13. Workflow of the proposed machine-learning programme.

6.6 Sensitivity analysis, SHAP feature importance and physical interpretation

Interpretation shall proceed on three levels. First, the feature importance of the model can be determined through SHAP (SHapley Additive exPlanations) method, which uses the Shapley value from cooperative game theory the only method that satisfies the conditions of local accuracy, missingness and consistency; the KernelSHAP method shall be used for the ANN and SVR models, as well as the TreeSHAP method for the RF and XGBoost models. Second, the dependence plots for the dosage of the SBR will be examined for signatures that indicate the type of relationship that is described in Section 5.3 of this paper. Finally, one-at-a-time sensitivity analyses will be performed for each of the features to determine if the dosage of SBR exhibited the same behavior as the Abrams method for the water-cement ratio, and a positive effect of age on the concrete. Each of these analyses is an indicator of the physical plausibility of the model; should the results of any of these analyses indicate a relationship between any of the features and the strength of the concrete that contradicts the expectations for such a relationship based on the physical science of cement-based materials for instance, if dosage of SBR was found to have a positive relationship with the strength of the concrete, or if the water-cement ratio was found to exhibit a positive marginal relationship with the strength of the concrete the model is to be rejected.

7. Limitations of the present study

The following limitations of the study will be discussed. First, no samples of either unmodified Portland cement or river sand were cast, so it is not possible to determine the contributions of each of these components to the improvement of the properties of the concrete. Second, because there were no replicates of the concrete, individual measurements of each cast concrete cube, and their standard deviations, it is not possible to discuss any statistical analyses of the properties of this concrete. Third, properties other than compressive strength and workability were not measured; properties of concrete that are improved by the addition of SBR latex include split tensile strength, flexural strength, and durability. Fourth, information regarding the specific characteristics of the latex was not collected. Fifth, while the specific gravity of the M-sand was measured as 2.56, 2.62 was used in the calculations to prepare the concrete. Finally, each of the concrete were prepared with only one grade of cement, with one dosage of water to cement by mass ratio and cured for only a single age.

8. Conclusions and recommendations

From the experimental evidence obtained in this study, the following conclusions are drawn.

- M20 grade cement concrete that satisfies the characteristic strength of 20 MPa after 28 days of curing can be prepared using manufactured sand as the complete fine aggregate at any dosage of SBR latex used (between 2 and 8% by mass of the cement).
- The workability of the SBR cements varied with latex dosage; it decreased from a slump of 85 mm at 2% latex to 110 mm at 6% latex to 95 mm at 8% latex.
- The compressive strength of the concrete followed the same pattern as workability. The concrete containing 6% SBR latex achieved the highest strength at 7 days (21.14 MPa) and 28 days (27.03 MPa) of age, and the only concrete whose strength was higher than the target mean strength of 26.6 MPa; the concrete containing 8% SBR latex achieved the lowest strengths at both ages. Thus, 6% SBR latex by mass of cement was found to be the optimum dosage of SBR latex in this study.
- The reason for the decrease in strength of the concrete at dosages higher than the optimum is thought to be due to the effect of entrained air and the compliance of the polymer phase in the concrete; further investigation is required to confirm this hypothesis.

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