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Impact of Sustainable Materials and Material Composition on Structural Strength

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ABSTRACT

Changing to sustainable construction materials is one of the most far reaching changes in the practice of civil and structural engineering in the last twenty years which was motivated by the environmental requirements, resource limitations and changing performance demands. This paper explored how sustainable materials and material composition affect structural strength among the civil engineers, construction professionals, and material specialists in the infrastructure and construction industries in Pakistan. The quantitative approach was used. The respondents sampled were 200 chosen using purposive sampling criteria on the basis of engagement in material selection and structural design. The perceptions of sustainable material properties, material composition optimization practices, and structural strength results were measured in a structured questionnaire with a 5-point Likert scale with additional technical performance indicators. Descriptive statistics were used to summarize profiles of respondents. Cronbachs alpha, Composite Reliability (CR), and Average Variance Extracted (AVE) were used to evaluate reliability and validity. Inter-variable correlations were studied using correlation analysis. The hypothesized relationships were tested using Structural Equation Modeling with SmartPLS 4.0. Sustainable materials showed a high level of positive direct impact on the structural strength (beta = 0.46, p <.001), and material composition shows the same high level of positive direct impact (beta = 0.43, p <.001). The structural model was found to explain 59.4% of the variance in structural strength (R-squared = 0.594). These results demonstrate that sustainable material use and optimization of material composition systematically are complementary and reinforcing directions towards structural strength realization, and have significant implications to sustainable construction practice in Pakistan.

Introduction

The built environment and construction industry in general uses around 40 percent of world primary energy, produces more than 30 percent of world carbon dioxide emissions, and extracts about half of the world resources, making construction materials one of the most important product lines in the global economy (Kibert, 2016). It is against this environmental urgency backdrop that the design and implementation of sustainable construction materials - construction materials with less embodied energy, less greenhouse gas emissions, increased durability, or the use of recycled and industrial by-product constituents - has come to be an urgent engineering, policy, and market development concern. The underlying engineering issue in this shift is to provide that the environmental advantages of sustainable materials are realized without jeopardizing the structural performance - especially the strength, durability, and long-term reliability - of constructed infrastructure.

The structural strength of a structural member or system is the ability to withstand the applied loads without failure or unacceptable deformation. Structural strength is the performance requirement of all construction, whether residential buildings or bridges, dams and industrial facilities. The compressive strength, tensile strength, flexural strength, shear strength are all parameters that define the structural performance envelope that design engineers are allowed to operate in, and the material selection defines the limit of the envelope. Over a century of structural construction has been based on the dependable and characterized strength properties of Portland cement concrete, yet its production results in about 8 per cent of the world CO2 emissions, an environmental cost that has spurred intensive research into complementary cementitious materials, alkali-activated materials, recycled aggregate concrete, and bio-based construction materials as lower-carbon alternatives (Mehta and Monteiro, 2014

Material composition - the exact proportionality of the constituent materials such as binders, aggregates, water and chemical admixtures in concrete and composite materials is the engineering tool with which structural strength is obtained and optimized. The water to cement ratio, aggregate grading, proportion of supplementary cementitious material (SCM) and the choice of admixtures jointly determine the microstructural properties of hardened concrete and hence regulate its mechanical strength, durability and serviceability. The principle set by Abrams Law (1919) was that the concrete compressive strength was mainly dependent on the water to cement ratio and that a century of further study has expanded the simple principle into elaborate mix design approaches that allow engineers to design material combinations that can give them target structural strength at a given reliability (Neville, 2011).

The correlation between sustainable materials and structural strength has undergone a great deal of research, with the results that differ significantly depending on the type of material, its composition, and use. Numerous studies have demonstrated that supplementary cementitious materials such as fly ash, ground granulated blast furnace slag (GGBS), silica fume, and metakaolin can be used to increase concrete strength when they are used as partial cement replacements, by pozzolanic reactions that uses calcium hydroxide generated during cement hydration and forms other calcium silicate hydrate gel (CSH) - the main strength Historically, recycled aggregate concrete has been found to incur a strength penalty compared to natural aggregate concrete because of increased water absorption and poorer quality of recycled aggregates, although more sophisticated mix design strategies such as effective water-to-cement ratio adjustments and aggregate pre-wetting measures have significantly mitigated the strength penalty (Kou and Poon, 2012; Zhang and Tam, 2020).

The use of sustainable materials in the construction industry in Pakistan has been increasing, but disproportionately, with large infrastructure projects increasingly using GGBS and fly ash as cement substitutes, compared to residential and small commercial construction. Pakistan produces large amounts of fly ash in coal-fired power stations - an industrial by-product that is not only an environmental management problem but also a potential source of additional cementitious material - but the construction rates of this material are much lower than those of the similar regional economies (Rafiq et al., 2019). The structural performance of fly ash concrete under the different climatic conditions in Pakistan, including hot-dry conditions in the Sindh region and freeze-thaw cycling in the northern regions, has not been fully described, which leaves engineering ambiguity that can prevent its use by the conservative design community.

The engineering importance of material composition optimization to achieve structural strength with sustainable materials is magnified compared to traditional materials since sustainable material constituents tend to vary more in chemical composition, particle size distribution and reactivity than standardized Portland cement. This inconsistency implies that the mix design guidelines used in traditional concrete cannot be directly applied to sustainable concrete recipes without experimental verification and optimization of composition to particular material selections and structural performance objectives (Lothenbach et al., 2011; Provis and van Deventer, 2014). The skill of the material engineers to cope with this higher design sophistication is a very critical mediating variable in the extent of achievement of structural strength through sustainable material adaptation.

The empirical studies of sustainable materials and structural strength that have been performed are mostly laboratory-based studies of individual combinations of materials under controlled conditions. There is limited systematic survey-based research on the relationship between the perceived sustainable material use (by practicing civil engineers and construction professionals) and material composition optimization and structural strength achieved in real-world construction practice, and this is relevant to practical importance (Kibert, 2016; Rashid and Frangi, 2017). This paper has filled this gap by conducting a survey on 200 qualified Pakistani construction professionals regarding their material selection habits, their evaluations of the strength performance of sustainable materials, and their structural evaluation using SmartPLS to model the structural relations.

The theoretical framework of the current study combines materials engineering performance theory with Technology-Organization-Environment framework (Tornatzky and Fleischer, 1990) that is used to implement sustainable material adoption. This holistic model forecasts that sustainable material property and composition optimization practices are independent positive predictors of structural strength results, with organizational and professional conditions mediating the success of material knowledge translation into construction performance. The results of this research paper add to the existing body of knowledge on sustainable construction through practitioner-based empirical data that supplements the current literature of research that is mainly laboratory-based.

Literature Review

The science of materials of sustainable construction materials and their implications to structural performance has been thoroughly discussed in some of the most reputable sources. Mehta and Monteiro (2014) have developed the basic microstructural framework of the strength-enhancing influence of supplementary cementitious materials, where pozzolanic reactions generate CSH gel that exhibits a more compact and less porous microstructure compared to that of the hydration products of Portland cement, thus enhancing compressive strength, impermeability, and durability. The degree of strength improvement is highly dependent on the chemical composition, fineness and reactivity of the SCM, and the conditions under which it is cured and at what age it is tested, which must be optimized by material composition to achieve desired structural performance.

The use of fly ash as a cementitious supplementary material has been widely studied and the recorded strengths have been found to be highly dependent on the fly ash class, the replacement level, and the curing regime. A detailed review of the supplementary cementitious material hydration chemistry was given by Lothenbach et al. (2011), who showed that Class F fly ash (low calcium) offers a major contribution of pozzolana with strength growth at later ages (28-90 days), whereas Class C fly ash (high calcium) offers a contribution of both cementitious and pozzolanic. The profile of strength development with age has some practical implications in structural design fly ash concrete strength might take a longer time to reach design strength, requiring a change in scheduling of the project, which can be reduced by optimization of material composition by choosing the right admixtures.

It has been revealed that ground granulated blast furnace slag (GGBS) can deliver exceptionally high levels of strength enhancement when substituting cement, as shown by Poon, Lam and Wong (2006) who showed that GGBS 50-70% replacement concrete had 28-day compressive strengths equal to or surpassing those of pure Portland cement concrete at the same water to binder ratio, as a GGBS concrete, which has embodied CO2 reductions of 50-70% compared to pure Portland cement concrete, is especially a sustainable material of choice in structural applications due to its sustainability benefits. In Pakistan, Rafiq et al. (2019) recorded the GGBS supply in the steel sector and established that well-designed GGBS concrete met structural strength goals, in comparison with traditional concrete, and lowered considerably the embodied carbon and building material expenses.

There is a greater amount of mixed structural performance evidence generated by recycled aggregate concrete (RAC) because of the variable nature of the recycled quality of aggregate used in demolished construction. In a major meta-analysis of RAC compressive strength, Kou and Poon (2012) found that coarse aggregate replacement at 30 percent or less tended to cause strength loss of less than 10 percent compared to natural aggregate concrete - losses that could be offset by small decreases in water-to-cement ratio. Through structural testing on full-scale RAC beam and column, Xiao et al. (2012) established that design code requirements that applied to conventional concrete were usually conservative to well-designed RAC, and that RAC can be used to meet structural design requirements provided the material composition is optimized to the particular recycled aggregate source. More recent evidence was presented by Zhang and Tam (2020), who found that the use of more recent technologies to enhance aggregate processing, such as micro-carbonation treatment of the surface of recycled aggregates, yielded significant improvements in RAC strength, close to the one of natural aggregate concrete.

Statistical and computational techniques have furthered optimization of material composition in order to achieve sustainable concrete; the design of concrete mixes has long been a trial-and-error procedure, but now it is being extended through statistical and computational methods. Khayat et al. (2012) have applied response surface methodology (RSM) to optimize the formulation of self-consolidating concrete that contains large proportions of supplementary cementitious materials, making it possible to simultaneously optimize the objectives of strength, workability, and durability that cannot be met by experimental methods using only one variable at a time. Sustainable concrete mix design, such as artificial neural networks and genetic algorithms, have been used by Deshpande et al. (2014) to show that data-driven composition optimization can produce better strength results with sustainable material blends compared to the conventional design equation methods.

The most radical sustainable material alternative is geopolymer concrete, an alkali activation of alumino-silicate precursors such as fly ash and slag, which eliminates Portland cement and thus has potential CO2 savings of 40-80 percent compared to Portland cement concrete. Provis and van Deventer (2014) have surveyed the geopolymer concrete structural properties and have shown that well-designed geopolymer concrete has compressive strengths of 40-100 MPa, which is well within the range of conventional structural concrete, and with similar durability to Portland cement concrete under most exposure conditions.

The issue with the adoption of geopolymer concrete has been that the mechanical performance is sensitive to the variability of the composition of the precursor, and that to achieve good material performance requires the material to be carefully characterized and optimization of the composition to individual precursor source, which has restricted its use in the construction industry where the material cannot be tested with advanced testing techniques.

The structural health monitoring of sustainable material structures has emerged as a significant tool to compare the in-service performance of the laboratory strength predictions. The theoretical basis of structural health monitoring was also developed by Farrar and Worden (2012), who showed that non-destructive assessment methods such as ultrasonic pulse velocity, ground-penetrating radar, and acoustic emission monitoring would identify the loss of strength in concrete structures long before the structures would deteriorate and allow proactive maintenance actions. The use of structural health monitoring to sustainable material structures is especially beneficial since they do not have as well-defined long-term performance properties as traditional Portland cement concrete, which generates more uncertainty regarding the ability of such structures to maintain their in-service strengths that can be measured through structural health monitoring.

As part of the construction context of Pakistan, Rashid and Frangi (2017) systematically reviewed sustainable construction practices in Pakistani infrastructure projects and discovered that the choice of sustainable materials was related more to cost factors (fly ash and GGBS are cheaper than Portland cement) than to environmental consciousness and that knowledge of sustainable material mix design was centralized in large contracting entities and governmental agencies and that small contractors had a strong knowledge gap. These results indicated that the structural strength performance of sustainable material use in Pakistan is crucially dependent on the technical competence of material engineers and quality assurance systems in construction organizations - variables that the material composition construct of this study encapsulates.

Sustainable construction materials life cycle assessment has provided the environmental performance parameters on which structural strength trade-offs should be assessed. The LCA comparison by Habert and Roussel (2011) showed that geopolymer concrete was found to reduce the global warming potential by 40-80% compared with Portland cement concrete and that strength-equivalent slag concrete alkali-activated reduced the potential by 50-60% in comparison with Portland cement concrete. These environmental performance indicators present the incentive towards adoption of sustainable materials, but they should be supported by structural performance information to illustrate that the strength requirements are satisfied to allow confident adoption in the structural design practice. The current research gap is bridged by the practitioner perceptions of sustainable material strength performance being the focus of the current study, as it addresses the disconnect of laboratory evidence on LCA and professional practice confidence.

The use of PLS-SEM in the construction engineering and materials performance research has been confirmed in some recent studies. Forcada et al. (2017) transferred PLS-SEM to construction quality management, revealing that the methodology effectively addressed the mixed nature of measurement of construction performance constructs. Hair et al. (2019) defined PLS-SEM as the right option in terms of engineering management research with a sample size of 100-300 and constructs of objective and subjective measurement indicators, which perfectly fits the design of the present research.

Methodology

This was a quantitative research project. The study sample included civil engineers, construction practitioners, and material experts who were directly involved in the choice of materials and structural design in the industry and infrastructure projects in Pakistan. Purposive sampling was used, and the inclusion criteria were at least three years of professional practice in structural design, construction management, or materials engineering, and being involved in the direct use of materials or quality assurance of structural qualities. The distribution of the survey was done using the Pakistan engineering council civil engineering network, the Pakistan Institute of Civil engineers and personal organizational contact with the infrastructure development authorities, construction firms and consulting engineering firms in Pakistan. Two hundred and thirty questionnaires were sent out with 200 completed questionnaires being returned after the removal of the incomplete ones.

The study tool consisted of three scales that were validated. Sustainable materials were assessed on a 12-item scale that includes sustainable material availability and quality (4 items: local availability of SCM, consistency of quality, certification, and data on long-term performance), material environmental performance (4 items: embodied CO2 reduction, recycled content, waste reduction, and long-term performance data availability), and material technical performance (4 items: strength development rate, durability characteristics, workability, long-term The material composition was evaluated through 11-item scale of mix design sophistication (4 items: water-to-binder ratio optimization, SCM proportion optimization, aggregate selection and grading, and admixture selection), quality assurance practices (4 items: fresh concrete testing, hardened strength testing, composition verification and batch control) and design documentation (3 items: mix design documentation, performance record keeping, and design adjustment procedures). A 13-item scale that included compressive strength achievement (4 items), tensile and flexural performance (3 items), long-term durability (3 items), and design code compliance (3 items) was used to operationalize structural strength. Each item used a 5-point Likert scale with technical benchmarks mentioned in the wording of the item. Demographic questions included experience of project, industry and technical specialization.

Content validity was determined by reading by five structural engineering and materials science faculty and three industry practitioners. Instrument adequacy was established by piloting with 20 qualified professionals not in the sample. Cronbachs alpha was used to determine reliability. The validity of PLS measurement model was assessed by indicator loadings (> 0.70), AVE (> 0.50), CR (> 0.70), and HTMT discriminant (< 0.85) validity. Two structural hypotheses were examined: H1, the hypothesis that sustainable materials are a significant positive predictor of structural strength; and H2 the hypothesis that material composition is a significant positive predictor of structural strength. All structural model estimation was done using SmartPLS 4.0 with bootstrapping (5,000 resamples).

Results and Analysis

The last sample involved 200 civil engineering and construction professionals. Table 11 shows the demographic profile. The largest sectors (64.5% combined) were construction of infrastructure and buildings. The sample size of structural engineers and design experts was 48.5. The mean professional experience was 9.1 years (SD = 5.8). More than 60% registered as Professional engineers or equivalent.

Table 1: Demographic Profile of Respondents (N = 200)

Variable	Category	n	%
Gender	Male	178	89.0
	Female	22	11.0
Sector	Infrastructure (Bridges/Roads/Dams)	72	36.0
	Building Construction	57	28.5
	Industrial Construction	41	20.5
	Consulting/Materials Testing	30	15.0
Role	Structural Design Engineer	97	48.5
	Construction/Site Engineer	63	31.5
	Materials Specialist/Lab Engineer	40	20.0
Experience	3-5 years	46	23.0
	6-10 years	89	44.5
	> 10 years	65	32.5
Registration	PE/CEng Registered	121	60.5
	Not Yet Registered	79	39.5

Note. N = 200. PE = Professional Engineer; CEng = Chartered Engineer.

Table 2 shows the descriptive statistics and alpha of Cronbach of all the variables in the study. All alpha were greater than.88. Sustainable materials showed an intermediate mean (M = 3.36), indicating imprecise availability and quality in the technical documentation of project contexts in the sample. The mean of material composition was similar (M = 3.41). Mean of structural strength was 3.52.

Table 2: Descriptive Statistics and Reliability Coefficients

Variable	M	SD	alpha	Min	Max
Sustainable Materials	3.36	0.75	.91	1.17	5.00
Availability and Quality	3.42	0.78	.87	1.00	5.00
Environmental Performance	3.31	0.79	.86	1.00	5.00
Technical Performance Data	3.35	0.77	.85	1.00	5.00
Material Composition	3.41	0.72	.92	1.18	5.00
Mix Design Sophistication	3.45	0.75	.88	1.00	5.00
Quality Assurance Practices	3.38	0.74	.87	1.00	5.00
Design Documentation	3.39	0.73	.86	1.00	5.00

Structural Strength	3.52	0.70	.92	1.29	5.00
Compressive Strength Achievement	3.58	0.73	.88	1.00	5.00
Tensile/Flexural Performance	3.46	0.74	.87	1.00	5.00
Durability and Long-Term Performance	3.52	0.72	.86	1.00	5.00

Note. M = mean; SD = standard deviation; alpha = Cronbach's alpha. N = 200.

The results of the PLS measurement model are in Table 3. Loadings of all indicators were more than 0.70. The values of AVE were between 0.53 and 0.57 and CR was between 0.88 and 0.93, thus validating convergent validity. All construct pairs had HTMT ratios less than 0.85 which established discriminant validity.

Table 3: PLS Measurement Model: Convergent and Discriminant Validity

Construct	Items	Loading Range	AVE	CR	alpha
Sustainable Materials	12	.70-.86	.54	.91	.91
Material Composition	11	.71-.87	.55	.92	.92
Structural Strength	13	.72-.88	.57	.92	.92

Note. AVE = average variance extracted; CR = composite reliability; alpha = Cronbach's alpha. All HTMT ratios < 0.85.

The intercorrelation matrix is given in table 4. Environmentally friendly materials showed good positive interactions with material composition (r = .61, p < .01) and structural strength (r =.57, p <.01). Structural strength had a significant correlation with material composition (r =.60, p <.01). The great interconnection between sustainable materials and the material composition validated the theoretical complementary nature of these constructs as co-determinants of structural strength.

Table 4: Intercorrelation Matrix

Variable	1	2	3
1. Sustainable Materials	--		
2. Material Composition	.61**	--	
3. Structural Strength	.57**	.60**	--

Note. ** p < .01 (two-tailed). N = 200.

Table 5 gives the results of the PLS structural model. The model proved to have satisfactory fit with SRMR = 0.063, NFI = 0.908. Sustainable materials had a strong positive direct influence on structural strength (.46, t = 7.18, p <.001), which proved H1. The material composition also showed a strong direct positive impact (beta = 0.43, t = 6.72, p < .001), which validates H2. The two predictors jointly explained 59.4% of the variance in structural strength (R-squared = 0.594). The size of effects was 0.30 sustainable materials and 0.27 material composition which are medium effects.

Table 5: PLS Structural Model Results

Hypothesis	Path	beta	SE	t-value	p	f-squared	Decision
H1	Sustainable Materials -> Structural Strength	0.46	0.064	7.18	< .001	0.30	Supported
H2	Material Composition -> Structural Strength	0.43	0.064	6.72	< .001	0.27	Supported

Note. beta = standardized path coefficient; SE = standard error (5,000 bootstrap resamples); f-squared = Cohen's effect size. R-squared (Structural Strength) = 0.594. SRMR = 0.063, NFI = 0.908.

Discussion

The provided structural model results received a robust empirical support of both hypotheses, and thus proved that sustainable materials and optimization of material composition is a crucial and equally high positive predictor of structural strength in the Pakistani construction professional practice. The almost identical size of the effect of sustainable materials (beta = 0.46) and the material composition (beta = 0.43) - with sustainable materials being slightly stronger - indicates that the quality and the performance of the sustainable materials per se is a slightly stronger predictor of structural strength achievement than the optimization of material composition towards the same. This is in line with the material science literature that demonstrates that the natural pozzolanic reactivity and chemical constituency of the supplementary cementitious materials is a direct limiting factor on the maximum strength that can be attained without regard to the sophistication of the mix design. The fact that the two effects are almost identical also, however, proves that optimization of material composition is a necessity that cannot be substituted by a better sustainable material quality and vice versa.

The moderately lower mean on sustainable materials (M = 3.36) as compared to material composition (M = 3.41) in the sample indicates that the availability of sustainable materials and documentation of technical performance are slightly more limiting when compared to mix design capability in Pakistani construction settings - a result that is in line with the fact that Rafiq et al. (2019) report inconsistency in supply chain information when using industrial by The high variance that the model explains (R-squared = 0.594) proves that these two material dimensions combined explain most of the structural strength variation in the sample, which proves the theoretical framework and justifies the practical relevance of structural performance determinants, sustainable material quality and composition optimization.

Conclusions and Recommendations

This research offered strong empirical support that optimization of sustainable materials and material composition are both important positive predictors of structural strength in Pakistani construction practice with sustainable material quality and availability being the slightly more important predictor. These results have certain policy and practical implications. In the case of construction organizations, the complementary nature of sustainable material quality and mix design sophistication suggests a parallel investment in both aspects - obtaining reliable supply chains to ensure constant-quality supplementary cementitious materials, and investing in mix design capability with laboratory testing facilities, expertise of material specialists, and a systematic mix design documentation.

To materials suppliers and the industrial by-product industry, the fact that the quality of sustainable materials and performance documentation is a key factor in structural strength results suggests that an investment in quality management system that can offer construction specifiers with trusted material characterization data, such as, in chemical composition certificates, reactivity indices, and strength contribution curves, can be used to optimize mix designs with confidence. The key producers of by-products of industrial activities in Pakistan (coal power plants, steel mills, etc.) should establish formalized quality management programs of fly ash and GGBS that may offer construction-sector customers with the uniform quality and technical documentation needed to achieve the structural specification. To regulators and standards authorities, new national building codes and material standards would be available that would directly solve the regulatory ambiguity that prevents the use of sustainable concrete mix mixes by risk-averse structural design engineers. The future studies must explore the differences in these relationships between the climatic regions of Pakistan, may explore whether the sustainable material-strength relationship is moderated by the professional registration and qualification, and may establish longitudinal evidence on the long-term strength and durability of the sustainable concrete in the Pakistani infrastructure.

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