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An integral based fuzzy approach to evaluate waste materials for concrete

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Abstract. Waste materials in concrete have been considered as one of the most important issues by the authorities, policy makers and researchers to maintain engineering serviceability in terms of economy, durability and sustainability. Therefore, evaluation and selection of waste materials with respect to multi criteria decision making (MCDM) for the construction industry has been gained importance for recovery and reuse. In this paper, Choquet integral based fuzzy approach is proposed for evaluating the most suitable waste materials with respect to compressive strength, tensile strength, flexural strength, compactness, toughness (resistivity for dynamic loads), water absorption and accessibility. On conclusion, waste tyre and silica fume were determined as the most suitable waste materials for concrete production. The obtained results are recommended to assist the authorities on configuring well designed strategies for construction industry with disposal materials.

Keywords: waste material; construction industry; fuzzy logic; multi criteria decision making; Choquet integral

1. Introduction

All engineering facilities are constructed by the idea of minimum cost, maximum serviceability and durability. Concrete is still the most adequate material in civil engineering industry to supply people optimum life space. It is composed of aggregate, binder (cement), sand and water. While, cement occupies 10%, sand and aggregate occupy 70% of total concrete volume; 5% of CO_2 emission of total CO_2 oscillation belongs to cement industry (Worel *et al.* 2001). These huge consumption amounts for concrete production lead to search for various alternative of concrete ingredients. Waste tyre, plastics like pet bottle, demolition waste, marble quarry waste, rice husk and silica fume can be used as waste materials in concrete for alternative concrete materials. During design phase, many engineering properties of concrete have to satisfy the designer needs in terms of durability, serviceability and cost. While durability and serviceability can be fulfilled by compressive strength, tensile strength, flexural strength, compactness, water absorption; cost can be fulfilled by accessibility. Optimum material mostly depends on optimum performance of these properties. There are many studies for material selection and applied method on the base of this aspect. Gönen *et al.* (2012) presents a comprehensive review on new waste material for construction industry. Skibniewski and Chao (1992) studied on advanced construction technology for two lower crane alternatives with analytic hierarchy process (AHP). Pan (2008) applied fuzzy AHP to select an appropriate bridge building to use material, workmanship and energy in the most effective manner. Advance shoring method was selected the most suitable and optimum construction method. Topcu (2004) proposed contractor selection model in the Turkish public sector by a multi-criteria decision model in terms of cost, time and quality. Kim *et al.* (2014) evaluated failure risk of excavation work with a fuzzy AHP. Human factor, material loading, site conditions and mobile equipment were evaluated with three illustrative cases. Urban pervious pavements were also studied. Ten experts declared their experiences about water management system and this information were used in stochastic simulations with MIVES methodology. Porous asphalt, porous concrete and interlocking concrete were considered with auxiliary complements like fuzzy AHP, Monte Carlo simulations and fuzzy sets. Jato-Espino *et al.* (2014b) presented a literature review of multi-criteria decision making methods in construction. 25 different methods were used for 11 different groups in construction. Deluka-Tibjas *et al.* (2013) revealed the basic points of multi-criteria decision making methods about transport infrastructure in their review paper. This paper disseminates importance of transport infrastructure in terms of planning, design, maintenance and reconstruction. Hopfe *et al.* (2013) implemented a case study related to multi-criteria decision making in building performance based on uncertainty information. It was emphasized that developed method contributed enhancing the information flow, minimizing risk and providing a framework for communication. Tavares *et al.* (2008) studied AHP to select the fire origin room considering 3 types of room with respect to six different criteria. Wong and Li (2008) apply AHP for selection of intelligent building system in terms of work efficiency, safety and cost effectiveness. Moreover, reliability, operating and maintenance cost were selected as sub-criteria. Askari *et al.* (2016) applied fuzzy based approach

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to evaluate semi-active magnetorheological dampers. In addition, fuzzy modelling is applied to evaluate damage detection (Aydin and Kisi 2015), predict shear strength of high strength concrete deep beams (Mohammadhassani *et al*. 2014, 2015). This paper proposes Choquet integral based fuzzy approach for evaluating the most suitable waste materials for construction industry. The aim of this paper is to present importance of waste materials selection in construction industry and recommend to assist the authorities on configuring well designed strategies with disposal materials. The rest of this paper is organized as follows: Section 2 critically analyzes the current state-of-the art in this research domain and includes the mathematical background of the proposed integral based fuzzy approach. Then, the application of the proposed approach to evaluate waste materials is presented in section 3. Results and discussion part reveals material order and reason of ranking in section 4. The conclusion is given in last section.

2. Material and method

In this section, firstly the definitions and related literature review for six waste materials are presented. After that, the proposed approach is explained.

2.1 Definitions and literature review for waste material

2.1.1 Waste tyre

The main properties of waste tyre is firstly abundant. Second, this material contributes more toughness capacity to concrete against to dynamic impact and vibrations (Li *et al*. 2004a). Then, it contributes plastic deformation capacity and impact resistance. For these reasons, this material can be used in pavements, highways and retaining walls by replacing with 15% aggregate (Li *et al*. 2004b). Toughness is also one of the most pioneer parameter to attract engineers to use this material. Toutanji (1996) investigated toughness and reported that contributes high amount of toughness to concrete according to control concrete. Strength, toughness and deformability of concrete were studied by Song *et al*. (2011). Twelve column specimens were produced with 0.6 mm and 1.0 mm rubber chips. Curvature of ductility arises 90% that means flexural capacity increases. It was concluded that toughness increases due to ductility therefore this material is optimum to dissipate seismic shaking.

2.1.2 General plastic wastes and bottles

The quantity of solid plastic waste is accumulating day by day. For example, 13.000 ton/day solid plastic pet bottle was wasted in 2005 in Bangkok (Panyakapo and Panyakapo 2008). It is reported that 87.000 tons' solid pet bottles were wasted in Korea in 2002 (Choi *et al*. 2005). Generally, annual pet bottle waste is around 10 million tons in 2007. This amount shows that nearly 250 milliards pet bottle is used every year on the world (Frigione 2010). For this huge amount waste of bottles, it is very important to recycle these types of materials in concrete for different purpose to decrease yield hazardous materials during production of cement and other materials in concrete. Akçaözü *et al*. (2010) use waste PET bottle as aggregate in light weight concrete and report that adding 0.3% and 1.5% of volumetric amount of shredded PET bottle decreases dead weight of concrete. Silva *et al*. (2005) study waste PET bottles as Cement Matrix. They emphasize that using this material has no negative influence on Ultimate Strength and Elastic Modulus. Furthermore, using PET bottles as different material gives better toughness ratio at 35 days' age while compare other age up to 150 days. Choi *et al*. (2005) use PET bottles as aggregate in concrete and compare with granulated blast furnace slag. In their study, fractions of PET bottle waste are used 5-15 mm and mix proportions are considered as 0%, 25%, 50% and 75% on the base of replacement ratio. They report that workability of concrete is increased with increasing volumetric ratio. Structural efficiency of concrete casted with PET bottle waste is optimum at the level of replacement ratio 75% on the base of 28-day compressive strength. Albano *et al*. (2009) study PET bottles as light weight aggregate and they investigate mechanical behavior and thermal degradation on the base of varying w/c ratio. It is reported that 10% replacement of this material contributes ductility of structure and best mechanical properties are obtained with 10% replacement ratio and 0.5 w/c ratio. Frigione (2010) uses PET bottles as fine aggregates. PET bottle is replaced 5% by weight of siliceous sand and then it is reported that using PET bottles shows similar workability and slightly low decrease at compressive strength and splitting tensile strength.

2.1.3 Demolition waste

It is predicted that generation of construction and demolition waste in EU per year around 450 million tons. This is the largest waste generation except for farm waste after harvesting (Rao *et al*. 2007). Topçu and Şengel (2004) study mechanical and physical properties of concrete casted with Waste Concrete Aggregate (WCA). It is reported that while replacing 30, 50, 70 and 100% of WCA with Natural Aggregate (NA). Concrete class of WCA, C16, used in concrete production. These amounts are mixed (Topçu and Şengel 2004) and then related benefits are reported as specific gravity of WCA is lower than NA, water absorption of WCA is higher than NA, compressive strength of WCA depends on mostly w/c ratio. Workability performance of WCA concrete depends on the amount of replacement ratio of WCA and it is observed that workability is decreased with increasing proportion of WCA. Furthermore, it is reported that specific gravity of WCA concrete is lower than NA concrete. Water absorption ratio of WCA concrete is much higher than water absorption of NA Concrete. This study is concluded that under this condition, concrete with WCA production is vital for environmental safety than using in concrete as inadequate aggregate for concrete (Topçu and Şengel 2004). According to review paper of Evangelista and Brito (2014), compressive strength of fine recycled aggregate concrete decreases from 42 MPa to 32 MPa with increasing replacement ratio while compare with concrete produced by fine natural aggregate. Maximum loss for study is 6.5 % in terms of compressive strength.

On the base of the same paper of Evangelista and Brito (2014), general perspective of compressive strength of concrete produced with Fine Recycled Aggregate (FRA) and Coarse Recycled Aggregate (CRA) is compared to prove contradiction with replacement ratio. While increasing the FRA ratio, compressive strength starts to decrease from 23 MPa to 22 MPa. There is a reverse relationship between substitution ratio of CRA and compressive strength. The demolished CRA are substituted in 0%, 50% and 100% by weight volume and then strength of concrete is obtained 21.5 MPa, 22.5 MPa and 24 MPa respectively. However, increase in CRA is about 4% and on the contrary decrease in FRA is about 12%. This differential amount is profitable for this type of production. Other important mechanical property of concrete is tensile strength; there is not a certain increase or decrease in tensile strength with arising replacement ratio. This increase and decrease depends completely on w/b ratio. For instance, if replacement ratios are considered 10%, 50%, 90% and 100%, it is reported that tensile strength values are 3.0 MPa, 3.1 MPa, 3.3 MPa and 3.4 MPa at 0.6 w/b ratio. Other example is pertinent to 0.4 w/b ratio, if replacement ratios are considered 10%, 50%, 90% and 100%, it is emphasized that tensile strength values are 4.9 MPa, 4.7 MPa, 4.5 MPa and 4.4 MPa. Chan and Sun (2006) report that fresh concrete that is prepared with Recycled Aggregate (RA) with replacement ratio 50% had relatively high initial slump for workability. Use of Fine RA as sand reduces the compressive strength and the elastic modulus but not considerable amount. Other impressive result for this study is related to shrinkage. It is reported that shrinkage of this type of concrete has not a remarkable increase on concrete with arising RA content. Wagih *et al.* (2013) use Recycled Concrete Aggregate in their studies at 25%, 50%, 75% and 100% amount. 100% replacement ratio results in only 10 % decrease. In their studies replacement ratio of RA results 6-13% reduction at compressive strength and arising replacement ratio, more than 50%, results a decrease between 15-23%. 100% replacement ratio of RA causes a decrease at Elasticity Modulus around 8%.

2.1.4 Marble waste

Marble waste production amount of quarry is approximately 80% of all extracted stone. Andre *et al.* (2014) investigate engineering properties of concrete produced by waste coarse marble aggregate (CMA). According to their study, CMA is replaced with increasing portion like 20%, 50% and 100% of total aggregate amount. There is not any remarkable change on behalf of durability among two group of specimens produced with CMA and NA. Andre *et al.* (2014) report a tiny decrease in terms of compressive strength at 28 days' age. According to the same study, carbonation depth is the same between concrete produced with CMA and NA also these specimens' show the same microstructure analogy. Durability performance and water absorption of concrete produced with CMA and NA specimens' also show the same performance. Binici *et al.* (2008) study engineering properties of concrete during fresh and hardened state of concrete produced with Granite and Marble Waste. They report that concrete produced with waste materials need plasticizer to obtain the same workability. Compressive strength and abrasion resistance of concrete are slightly affected by waste materials. Concrete specimens produced with marble waste show best abrasion resistance performance. Using marble and granite waste in concrete decreases chloride penetration approximately 70%. According to this study, addition of marble waste into concrete improves many properties of concrete like mechanical properties, workability and chemical resistance of conventional concrete. Gameiro *et al.* (2014) investigate durability and workability of concrete produced by waste marble. It is reported that optimum waste marble ratio in concrete is around 20% to obtain ideal concrete specimen and to converge very close to conventional concrete properties. Topçu *et al.* (2009) study effect of Marble Dust (MD) in Self Compacting Concrete (SCC). MD is replaced with sand in concrete at various amounts from 0 to 300 kg/m^3. 200 kg/m^3 MD amount is developed engineering properties of concrete in terms of compressive strength, flexural strength and compactness. Ergün (2011) reports basic procedures and results of laboratory investigation of concrete produced with Waste Marble Powder (WMP) replaced with cement. Partial replacement procedure is followed like 5% WMP, 5% WMP and 10% diatomite. Among these mix design, 5% WMP develops engineering properties of concrete specimens produced by WMP. Gesoğlu *et al.* (2012) use Marble Dust (MD) in Self Compacting Concrete (SCC) with a constant w/b ratio equal to 0.35. Results of this study showes that high amount replacement ratio MD has a small reverse effect on SCC. However, mechanical properties and transportation properties of concrete is developed with MD. Binary and ternary group of concrete specimens succeeded scientific target in terms of compressive strength and split tensile strength. Aliabdo *et al.* (2014) investigate effect of marble dust as a cement material and as a sand material in concrete. According to this report, replacement ratio is used incremental amount like 0%, 5%, 7.5%, 10% and 15%. Particularly, using waste marble dust in concrete as sand has more contribution to concrete than using as cement. Hebhoub *et al.* (2011) investigate the effect of using waste marble aggregate in concrete as natural aggregate. It is reported that using waste marble aggregate in concrete resulted an increase in compressive strength and tensile strength. Aruntaş *et al.* (2010) study Waste Marble Dust (WMD) in cement production. According to this study, WMD is used at different substitution ratio like 2.5%, 5%, 7.5% and 10% by weight. It is reported that 10% WMD comply with EN 197-1 standard. Also this study emphasize that this material does not affect setting time. Cemalgil and Onat (2016) investigate the effect of waste marble dust as a binder material in concrete and waste marble aggregate in concrete as a natural aggregate on compressive strength and abrasion resistance. Even if, waste marble dust has a high water absorption ratio, both compressive strength and abrasion resistance values are nearly the same as reference concrete specimens.

2.1.5 Rice husk

Zerbino *et al.* (2011) study grinded and natural rice husk ash. Grinded rice husk ash (GRHA) is replaced with cement 25% and Natural rice husk ash is replaced with cement 15% amount by weight. NRHA achieve predicted target in terms of mechanical and durability while compared with control concrete. Grinded shows better performance in terms of compressive strength than natural RHA. Venkatanarayanan and Rangaraju (2015) investigate effect of Ungrounded Low-Carbon Grinded Rice Husk Ash (URHA) in concrete replaced by puzzolanic material. Optimum amount is 7.5% for GRHA Concrete. It is reported that 7.5% replacement ratio developed all engineering properties. However, it is emphasized for their study that more than this amount has no effect on concrete specimens. Ferraro and Nanni (2012) implement an investigation about Off-White Rice Husk Ash (OWRHA) as binder material like cement. Corrosion resistance, strength, porosity and thermal conductivity are investigated. It is reported that 15% replacement of OWRHA with White Portland Cement has not any negative effect on strength parameters. Chao-Lung *et al*. (2011) investigate compressive strength, electrical resistivity and ultrasonic pulse velocity. Non-ground Rice Husk Ash is used in this study. It is reported that 20% of RHA at 0.35 w/b ratio show best performance in terms of all engineering properties that are investigated in this study. Especially, 47-66 MPa target level is achieved in their study. Giaccio *et al*. (2007) discuss mechanical engineering properties of concrete produced by RHA. Normal and high-strength concrete are compared in their study especially at lower w/b ratio. It is reported that concrete specimen showed brittle behavior at high replacement ratio. Furthermore, it is emphasized that this brittle behavior results in brittle failure mechanism of concrete under compression force. Besides, flexural strength and fracture energy are decreased with increasing substitution rate of RHA according to the same study. Yüzer *et al*. (2013) investigate effect of RHA in normal strength concrete in terms of compressive strength. It is reported that replacement of RHA decreased density and compressive strength but this material develops physical and thermoplastic properties of concrete.

2.1.6 Silica fume

Silica Fume (SF) is a yield material produced by the end of ferrosilicon industrial activities. This material is composed of fine, amorphous and mineral admixture (Chandra and Berntsson, 1996). Popovics (1993) investigates flow, ultrasonic pulse velocity and strength of concrete mortars produced with SF replaced by 5% by weight as cement. It is reported that results of this study satisfied to use SF in concrete on behalf of hydraulic binder. Bagheri *et al*. (2013) study SF in concrete to see strength development and durability. Silica fume shows better performance in terms of compressive strength and also silica fume has lower water needs among binary and ternary specimens. Alexander and Magee (1999) study Condensed Silica Fume (CSF) in concrete in terms of short-term durability and strength parameters. In this study 30, 40 and 50 MPa strength values are target for control specimens and they compare concrete produced with CSF with these values. It is reported that 10% CSF as binder shows optimum performance among other studied parameters. The researchers achieve their compressive strength target like 44, 57 and 64 MPa. Babu and Prakash (1995) implement a series of experiments to disseminate better technical information about efficiency of high strength concrete produced with Silica Fume (SF). Efficiency concept is used in their studies. It is reported that when SF is replaced between 5-40%, overall efficiency varies between 2.28-6.85 and percentage efficiency changes between 0.37-1.11. Çakır and Sofyanlı (2015) investigate contribution of SF in concrete replaced by 0%, 5% and 10%. Compressive strength increase with replacement ratio of 5% and 10% of SF. It is reported that water absorption ratio of concrete produced with Recycled Aggregates and SF is decreased at further ages. However, this change effects less amount the concrete produced with only SF than the concrete produced with binary materials. Bhanja and Sengupta (2005) seek for asset of SF addition into concrete at constant w/b ratio in terms of flexural strength, split tensile strength and compressive strength. It is reported that optimal results are obtained at different ratio for different parameters such as split tensile strength. Giner *et al*. (2011) investigate dynamic effect of concrete produced with SF replacement. They implement a series of tests to reveal the effect of SF replacement in concrete in terms of static and dynamic modulus, resonant frequencies and damping ratio of concrete. It is reported that dynamic modulus of elasticity is slightly increased with substitution of SF. Flexural strength of concrete is not affected significantly by SF replacement with cement. It is emphasized that substitution of increased amount of SF result in lower dynamic modulus of elasticity, higher compressive strength and nearly the same flexural strength. Siddique (2011) gather valuable technical data about hardened properties of concrete produced with SF replacement by hydraulic binder. Siddique indicate that SF has a better effect on flexural strength and secant modulus than split tensile strength. Moreover, SF does not have nearly any effect on flexural strength with increasing SF amount. Karatas *et al*. (2010) add SF to Self-Compacting Concrete (SCC) and reported that highest normalized bond strength is obtained by adding 5% SF to concrete produced beam element. Turk *et al*. (2012) implement a comparative experimental study to see the effect of SF and fly ash on compressive strength of concrete. It is reported that highest compressive strength is obtained by using 15% SF in concrete as a binder material.

2.2 Fuzzy Choquet integral

Fuzzy logic, developed in 1965 by Lotfi A. Zadeh, is robust tool to deal with the vagueness and uncertainty of human judgments and assessment in making decisions process (Celik *et al*. 2013, Akyuz and Celik 2015, Gul *et al*. 2016a, Gul and Guneri 2016). In real world decision making problems, especially many decisions, involve imprecision since goals, constraints, and possible actions are not known precisely (Zadeh 1965). Instead of combining various experiences, opinions, ideas and motivations of an individual or group decision makers, it is better to convert the linguistic terms into fuzzy numbers.

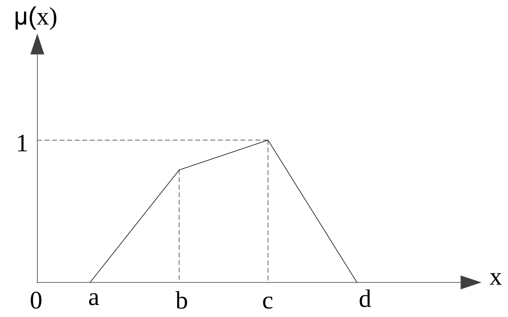

Fig 1. Trapezoidal fuzzy number

Therefore, the problems of group decision-making have necessary produced with fuzzy numbers in practice. A fuzzy number M of the universe of discourse X may be characterized by a trapezoidal distribution parametrized by (a, b, c, d) where $a \leq b \leq c \leq d$ presented in Fig. 1.

Fuzzy Choquet integral is an MCDM approach which is based on fuzzy sets to measure the expected effectiveness of alternatives with respect to hierarchical criteria. Different applications have been presented by researcher using Choquet integral. A decision-based fusion system based on the uncertainty approach using generalized Choquet integral by fuzzy is developed (Auephanwiriyakul *et al.* 2002). Chiou and Tzeng (2002) combine fuzzy AHP and fuzzy Choquet integral to assess the artificial performances of green engineering strategies for marine products processors. Aydin *et al.* (2016) also propose AHP and Choquet integral based on fuzzy sets for rail transit evaluation. Tzeng *et al.* (2005) apply Choquet integral to evaluate the enterprise intranet web sites' performances. Karsak (2005) uses Choquet integral to robot selection problem. Angilella et al. (2010) develop a non-additive robust ordinal regression on a set of alternatives whose utility is evaluated in terms of Choquet integral which permits to the interaction among criteria. Büyüközkan *et al.* (2009) develop two-additive Choquet integral for the evaluation of a fourth-party logistics provider operating models. Tan and Chen (2010) propose an intuitionistic fuzzy Choquet integral on MCDM, where interactions phenomena among the decision making criteria are considered. Özkır *et al.* (2015) propose a three stage methodology for evaluating collection location of e-waste. Demirel *et al.* (2010) use Choquet integral for warehouse location selection problem. Hu and Chen (2010) propose three Choquet integral-based hierarchical networks with the pre-specified hierarchical structure for evaluating customer service perceptions in fast food stores. Yazgan *et al.* (2010) adapt a Choquet integral to an Analytic Network Process (ANP) model and apply on a dispatching rule selection problem. Tan (2011) presents a Choquet integral and Technique for Order Preference by Similarity Ideal Solution (TOPSIS) based multi-criteria interval-valued intuitionist fuzzy group decision making method. Jang (2012) proposes a Choquet integral as an interval-valued aggregation operator. Tsai and Lu (2006) evaluate services of quality using generalized fuzzy Choquet integral. Ashayeri *et al.* (2012) present an intuitionistic fuzzy Choquet integral for supply chain partner and configuration selection problem. To the best of authors' knowledge, this is the first study that applies integral based fuzzy Choquet approach for evaluating the most suitable waste materials for construction industry.

The proposed approach includes eight steps (Tsai *et al.* 2006, Demirel *et al.* 2010, Aydin *et al.* 2015):

Step 1. The degree of importance ($\tilde{A}_i^l$), perceived waste materials levels ($\tilde{C}_i^l$) and the tolerance zone ($\tilde{T}_i^l$) are determined based on six experts' decisions.

Step 2. Average $\tilde{A}_i^l$, $\tilde{C}_i^l$ and $\tilde{T}_i^l$ into $\tilde{A}_i$ and $\tilde{T}_i$ are calculated using Eq. (1)

$$\tilde{A}_i = \frac{\sum_{k=1}^{K} \tilde{A}_i^l}{K} = \left(\frac{\sum_{k=1}^{K} a_{i1}^l}{K}, \frac{\sum_{k=1}^{K} a_{i2}^l}{K}, \frac{\sum_{k=1}^{K} a_{i3}^l}{K}, \frac{\sum_{k=1}^{K} a_{i4}^l}{K} \right) \quad (1)$$

Step 3. The waste materials level of each criterion is normalized using Eq. (2)

$$\tilde{e}_i = \left\| E_i^{\alpha} \right\|_{\alpha\in[0,1]} = \Big\|_{\alpha\in[0,1]} \left[e_{i,\alpha}^-, e_{i,\alpha}^+ \right] \quad (2)$$

where $e_i \in E(S)$ is a fuzzy-valued function $\tilde{E}(S)$ is the set of all fuzzy-valued functions

$$\tilde{e}_i = \Big\|_{\alpha\in[0,1]} \left[e_{i,\alpha}^-, e_{i,\alpha}^+ \right] = \frac{\bar{S}_i^{\alpha} - \bar{T}_i^{\alpha} + [1,1]}{2},$$ $\bar{S}_i^{\alpha}, \bar{T}_i^{\alpha}$ are α-level cuts of $\bar{S}_i^{\alpha}$ and $\bar{T}_i^{\alpha}$ for all [0,1].

Step 4. The waste materials level of criterion j is calculated using Eq. (3)

$$(C)\int \tilde{e}d\tilde{h} = \Big\|_{\alpha\in[0,1]} \left[(C)\int e_{\alpha}^- dh_{\alpha}^-, (C)\int e_{\alpha}^+ dh_{\alpha}^+ \right] \quad (3)$$

where

$\bar{h}_i : P(S) \to I(R), \bar{h}_i = \left[h_i^-, h_i^+ \right], \bar{h}_i = \left[h_{i,\alpha}^-, h_{i,\alpha}^+ \right], \bar{d}_i : S \to I(R^+)$,

and $e_i = \left[e_i^-, e_i^+ \right]$ for $i = 1, \ldots, n$

A λ value and the fuzzy measures $h(RT_{(i)})$ is calculated and these are obtained from the following Eqs. (4)-(6) (Sugeno 1974, Ishii and Sugeno 1985)

$$h(RT_{(n)}) = h(\{s_{(n)}\}) = h_n \quad (4)$$

$$g(RT_{(i)}) = g_i + g(RT_{(i+1)}) + \lambda g_i g(RT_{(i+1)}) \quad (5)$$

where

$$1 \leq i \leq n$$

$$1 = h(S) = \begin{cases} 1/\lambda \left\{ \prod_{i=1}^{n} [1 + \lambda h(RT_i)] - 1 \right\} & if \ \lambda \neq 0 \\ \sum_{i=1}^{n} h(RT_i) & \lambda = 0, \end{cases} \quad (6)$$

where $A_i \cap A_j = \varnothing$ for all i, j=1,…,n and $i \neq j$ and $\lambda \in (-1, \infty]$. e is fuzzy measure on S. The Choquet integral of a function, $e: S \rightarrow [0,1]$ with respect to fuzzy measures e is defined by

$$(C)\int edh = \sum_{i=1}^{n}\left(\left(e\left(s_{(i)}\right)\right) - \left(e\left(s_{(i-1)}\right)\right)\right)e\left(RT_{(i)}\right) \tag{7}$$

where
$0 \le e(s_{(1)}) \le e(s_{(2)}) \le ... \le e(s_{(n)}) \le 1, e(s_{(0)}) = 0 \text{ and } RT_{(i)} = \{s_{(i)}, ..., s_{(n)}\}$.

Step 5. All waste materials levels are combined by utilizing a hierarchical process implementing the generalized Choquet integral using Eq. (8). The all waste materials result in a fuzzy number, $\tilde{V}$

$$\left.\begin{array}{l} maincriterion_{(1)} = (C)\int edg \\ \vdots \\ maincriterion_{(m)} = (C)\int edg \end{array}\right\rangle V = (C)\int maincriterion\ dg \tag{8}$$

Step 6. The defuzzification of the fuzzy number

$$\tilde{Y} = \left(a_1, a_2, a_3, a_4\right) \tag{9}$$

is done with respect to Eq. (9) and the waste materials are compared.

$$F(\tilde{A}) = \frac{a_1 + a_2 + a_3 + a_4}{4} \tag{10}$$

Step 7. The weak and advantageous criteria among the waste materials are calculated. The bigger value means the better levels.

3. Application of the proposed approach

In this section, the waste material based on experts' decisions is determined by using fuzzy Choquet integral methodology. Fuzzy sets are proposed by Zadeh (1965) and it is widely used in MCDM problems (Celik *et al*. 2015). MCDM problems includes both quantitative and qualitative criteria that use imprecise data and human judgments, hence, fuzzy set theory can be used to solve these problems (Kaya 2012, Erdogan and Kaya 2015, Gul *et al*. 2017). The steps of the application to evaluate waste materials are as follows:

Step 1. A trapezoidal fuzzy number is usually adopted to express the decision maker's evaluation on alternatives with respect to each criterion and can represent more general situations. Trapezoidal fuzzy numbers are applied to waste material for quantifying and evaluating the importance weight of the criteria the linguistic terms reply by experts and it is shown in Table 1.

The importance weight of criteria and each waste material linguistic evaluation with respect to each criterion is presented in Table 1 and Table 2, respectively.

Step 2. Table 4 present importance weights of the criteria based on six experts' decision. In this step, experts are selected from different universities which have academic papers on waste materials. This common point

Table 1 The linguistic terms and fuzzy numbers (Topçu *et al*. 2009, Topçu 2004, Toutanji 1996, Tsai and Lu 2006, Tzeng *et al*. 2005, Venkatanarayan and Rangaraju 2005)

Waste Materials	Criteria	Fuzzy numbers
Extra Low (EL)	Extra Unimportant (EU)	(0,0,0,0)
Very Low (VL)	Very Unimportant (VU)	(0,0.01,0.02,0.07)
Low (L)	Unimportant (U)	(0.04,0.1,0.18,0.23)
Slightly Low (SL)	Slightly Unimportant (SU)	(0.17,0.22,0.36,0.42)
Middle (M)	Medium (M)	(0.32,0.42,0.58,0.65)
Slightly High (SH)	Slightly Important (SI)	(0.58,0.63,0.8,0.86)
High (H)	High Important (HI)	(0.72,0.78,0.92,0.97)
Very High (VH)	Very Important (VI)	(0.93,0.98,0.98,1.0)
Extra High (EH)	Extra Important (EI)	(1,1,1,1)

Table 2 Individual importance of criteria

	EXPERT 1	EXPERT 2	EXPERT 3	EXPERT 4	EXPERT 5	EXPERT 6
COMPRESSIVE STRENGTH (C1)	VI	EI	EI	EI	EI	EI
TENSILE STRENGTH (C2)	M	HI	M	HI	L	M
FLEXURAL STRENGTH (C3)	M	HI	SI	VI	HI	HI
COMPACTNESS (C4)	VI	VI	VI	EI	HI	EI
TOUGHNESS (C5)	VI	SI	M	VI	U	VI
WATER ABSORPTION (C6)	HI	M	VI	EU	SI	VI
ACCESSIBILITY (C7)	HI	EI	HI	EI	VI	HI

Table 3 Waste materials linguistic evaluation

	RICE HUSK ASH	WASTE TYRE	DEMOLITON WASTE	SILICA FUME	PLASTICS	MARBLE WASTE
C1	H, H, H, VH, VH, SH	EL, M, L, EL, EL, VL	VL, SL, M, H, SH, VL	VH, VH, VH, EH, VH, EH	VL, L, L, M, SL, L	L, SH, SH, EH, VH, H
C2	L, SH, H, H, M, SH	EL, L, M, L, L, L	VL, M, M, M, M, VL	SL, H, VH, H, SH, H	VL, SH, M, SH, L, M	VL, H, SH, H, M, SH
C3	L, SL, H, H, M, SH	EL, EL, L, L, L, SL	VL, L, M, M, M, VL	SL, VH, VH, H, H, H	VL, M, L, SH, M, M	VL, SH, SH, H, SH, SH
C4	M, VH, VL, SL, SH, L	SH, SH, SH, EL, VL, VL	H, VH, SL, M, H, L	H, VL, VL, EL, M, VL	H, M, M, VL, L, L	M, H, VL, VL, M, L
C5	VL, SH, VL, M, L, L	H, H, VH, SH, VH, H	VL, L, L, M, M, VL	SL, M, VL, M, M, M	H, H, H, H, SH, M	VL, SL, VL, SL, M, L
C6	M, VH, L, VL, VL, H	EL, M, EL, M, M, L	H, VH, M, L, M, EL	H, VL, H, EL, VL, EH	L, H, EL, EH, M, L	L, H, H, VL, L, M
C7	M, H, SL, L, M, L	L, SH, SL, SH, EH, SH	L, L, H, SL, H, H	SH, VH, L, SH, VH, L	L, EH, H, VH, EH, VH	L, SL, H, EH, VH, M

eliminates their bias about other materials. Table 5 presents evaluations based on group decision making. The tolerance zone for each sub-criterion is obtained the combination of the lower and upper linguistic value of tolerance zone. For example, the tolerance zone of the C1 is comprise of the first two number of (0.06, 0.088, 0.13, 0.158) and the last two fuzzy number of (0.953, 0.987, 0.987, 1) respectively. The tolerance zone is determined as (0.06, 0.088, 0.987, 1).

Step 3 and Step 4. The results of the proposed approach for α=0 and α=1 is given in Table 7. For example, the value (0.383, 0.418, 0.916, 0.951) of "A1 and sub-criterion C1" is

Table 4 Fuzzy importance weights of the criteria

	Expert 1	Expert 2	Expert 3	Expert 4
C1	(0.93,0.98,0.98,1)	(1,1,1,1)	(1,1,1,1)	(1,1,1,1)
C2	(0.32,0.42,0.58,0.65)	(0.72,0.78,0.92,0.97)	(0.32,0.42,0.58,0.65)	(0.72,0.78,0.92,0.97)
C3	(0.32,0.42,0.58,0.65)	(0.72,0.78,0.92,0.97)	(0.58,0.63,0.8,0.86)	(0.93,0.98,0.98,1)
C4	(0.93,0.98,0.98,1)	(0.93,0.98,0.98,1)	(0.93,0.98,0.98,1)	(1,1,1,1)
C5	(0.93,0.98,0.98,1)	(0.58,0.63,0.8,0.86)	(0.32,0.42,0.58,0.65)	(0.93,0.98,0.98,1)
C6	(0.72,0.78,0.92,0.97)	(0.32,0.42,0.58,0.65)	(0.93,0.98,0.98,1)	(0,0,0,0)
C7	(0.72,0.78,0.92,0.97)	(1,1,1,1)	(0.72,0.78,0.92,0.97)	(1,1,1,1)
	Expert 5	Expert 6	Aggregated	
C1	(1,1,1,1)	(1,1,1,1)	(0.988,0.997,0.997,1)	
C2	(0.04,0.1,0.18,0.23)	(0.32,0.42,0.58,0.65)	(0.407,0.487,0.627,0.687)	
C3	(0.72,0.78,0.92,0.97)	(0.72,0.78,0.92,0.97)	(0.665,0.728,0.853,0.903)	
C4	(0.72,0.78,0.92,0.97)	(1,1,1,1)	(0.918,0.953,0.977,0.995)	
C5	(0.04,0.1,0.18,0.23)	(0.93,0.98,0.98,1)	(0.622,0.682,0.75,0.79)	
C6	(0.58,0.63,0.8,0.86)	(0.93,0.98,0.98,1)	(0.58,0.632,0.71,0.747)	
C7	(0.93,0.98,0.98,1)	(0.72,0.78,0.92,0.97)	(0.848,0.887,0.957,0.985)	

Table 5 Fuzzy waste materials evaluation

	The Combined Tolerance Zone	RICE HUSK ASH	WASTE TYRE	DEMOLITION WASTE	SILICA FUME	PLASTICS	MARBLE WASTE
C1	(0.06,0.088,0.987,1)	(0.767,0.822,0.92,0.962)	(0.06,0.088,0.13,0.158)	(0.298,0.345,0.45,0.507)	(0.953,0.987,0.987,1)	(0.102,0.158,0.25,0.305)	(0.642,0.687,0.78,0.82)
C2	(0.08,0.137,0.817,0.865)	(0.493,0.557,0.7,0.757)	(0.08,0.137,0.217,0.262)	(0.213,0.283,0.393,0.457)	(0.64,0.695,0.817,0.865)	(0.307,0.368,0.493,0.553)	(0.487,0.542,0.673,0.73)
C3	(0.048,0.087,0.847,0.888)	(0.425,0.488,0.627,0.683)	(0.048,0.087,0.15,0.185)	(0.167,0.23,0.327,0.387)	(0.698,0.753,0.847,0.888)	(0.263,0.333,0.457,0.518)	(0.507,0.552,0.69,0.747)
C4	(0.173,0.205,0.657,0.707)	(0.34,0.393,0.487,0.538)	(0.29,0.318,0.407,0.453)	(0.483,0.547,0.657,0.707)	(0.173,0.205,0.26,0.305)	(0.24,0.305,0.41,0.467)	(0.233,0.29,0.383,0.44)
C5	(0.117,0.163,0.92,0.962)	(0.163,0.212,0.297,0.352)	(0.767,0.822,0.92,0.962)	(0.12,0.177,0.26,0.317)	(0.242,0.318,0.45,0.515)	(0.63,0.695,0.843,0.898)	(0.117,0.163,0.253,0.31)
C6	(0.167,0.227,0.54,0.583)	(0.335,0.383,0.45,0.498)	(0.167,0.227,0.32,0.363)	(0.388,0.45,0.54,0.583)	(0.407,0.43,0.48,0.513)	(0.353,0.4,0.477,0.513)	(0.307,0.365,0.467,0.52)
C7	(0.268,0.34,0.843,0.867)	(0.268,0.34,0.467,0.525)	(0.492,0.535,0.657,0.705)	(0.402,0.46,0.58,0.632)	(0.517,0.57,0.653,0.697)	(0.77,0.807,0.843,0.867)	(0.53,0.583,0.67,0.712)

calculated as follows

$$f, f_i^{\alpha} = \left[f_{i,\alpha}^{-}, f_{i,\alpha}^{+} \right] = \frac{(0.767, 0.962) - (0.06, 1) + (1,1)}{2} = (0.383, 0.951) \text{ where } \alpha = 0$$

$$f, f_i^{\alpha} = \left[f_{i,\alpha}^{-}, f_{i,\alpha}^{+} \right] = \frac{(0.822, 0.920) - (0.088, 0.987) + (1,1)}{2} = (0.418, 0.916) \text{ where } \alpha = 1$$

$$= (0.383,\ 0.418,\ 0.916,\ 0.951)$$

Step 5. Table 6 summarize the whole fuzzy measures and λ values, which are calculated in the same way above and it include the normalized discrepancies and waste materials values. The combined values of the proposed approach for criterion C are computed as same way.

Step 6. The fuzzy and defuzzification values of the waste materials are calculated and the result of the proposed approach is presented in Table 7.

Step 7. From Table 7, the defuzzification values of waste materials using proposed approach are determined as 0.667, 0.728, 0.56, 0.724, 0.65 and 0.459. According to the results, waste tyre and silica fume are selected as the best and second most appropriate waste materials. The other ranking of the waste materials from third to six is determined as rice husk ash, general plastics and pet bottles, demolition waste and marble waste, respectively.

Step 8. Finally, the advantageous criteria of the six waste materials are signed as bold in Table 7.

4. Results and discussion

The results show that waste tyre yields the most adequate waste material with a slight difference from silica fume. Waste tyre has 0.728 numeric ranking but silica fume has 0.724. This difference occurs due to advantage of toughness. Toughness is the resistivity property for dynamic loads. Rubber is the most suitable material to absorb this effect. Only rubber and plastics have this property. However, rubber is better than plastics to absorb dynamic shaking according to literature (Worrel *et al*. 2001, Skibniewski and Chao 1992, Topcu 2004, Pan 2008). Furthermore, other asset of rubber chips in concrete is to increase flexural capacity of concrete columns according to Song *et al*. (2011). This contribution is 90 % to concrete columns (Topcu 2004). This property is also another positive effect for rubber tyre to be number one in the classification. Silica fume is also another suitable waste material for using in concrete on behalf of fineness. Fineness gives this material to make a strong bonding between other materials in concrete. Less amount of cement is enough to prepare high strength concrete, if silica fume is replaced with ordinary cement. Except for toughness property, there is no reason for silica fume to be 2nd material. Rice husk ash is the 3rd material with 0.667

Table 6 Fuzzy measure for α=0 and α=1

	A_1		A_2		A_3		A_4		A_5		A_6	
α=0	$g^-(A_{(i)})$	$g^+(A_{(i)})$	$g^-(A_{(i)})$	$g^+(A_{(i)})$	$g^-(A_{(i)})$	$g^+(A_{(i)})$	$g^-(A_{(i)})$	$g^+(A_{(i)})$	$g^-(A_{(i)})$	$g^+(A_{(i)})$	$g^-(A_{(i)})$	$g^+(A_{(i)})$
Λ	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00
$g(A_{(1)})$	0.99	1.00	1.00	1.00	1.00	1.00	0.99	1.00	1.00	1.00	1.00	1.00
$g(A_{(2)})$	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
$g(A_{(3)})$	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
$g(A_{(4)})$	1.00	1.00	1.00	1.00	0.97	1.00	1.00	1.00	1.00	1.00	1.00	1.00
$g(A_{(5)})$	1.00	1.00	0.62	0.79	1.00	1.00	1.00	1.00	0.98	0.79	1.00	1.00
$g(A_{(6)})$	1.00	1.00	0.98	1.00	0.58	0.75	1.00	1.00	0.94	1.00	0.58	0.75
$g(A_{(7)})$	1.00	1.00	0.94	1.00	0.99	1.00	1.00	1.00	0.85	1.00	0.94	1.00
α=1	A_1		A_2		A_3		A_4		A_5		A_6	
λ	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00
$g(A_{(1)})$	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
$g(A_{(2)})$	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
$g(A_{(3)})$	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
$g(A_{(4)})$	1.00	1.00	1.00	1.00	0.98	0.99	1.00	1.00	1.00	1.00	1.00	1.00
$g(A_{(5)})$	1.00	1.00	0.68	0.75	1.00	1.00	1.00	1.00	0.99	0.75	1.00	1.00
$g(A_{(6)})$	1.00	1.00	0.99	1.00	0.63	0.71	1.00	1.00	0.96	1.00	0.63	0.71
$g(A_{(7)})$	1.00	1.00	0.96	0.99	1.00	1.00	1.00	1.00	0.89	0.99	0.96	0.99

Table 7 Defuzzified values of waste materials

Criteria	$(C)\int \tilde{f}d\tilde{g}$						$(C)\int fdg$ Defuzzified					
	RICE HUSKASH	WASTE TYRE	DEMOLIITON WASTE	SILICA FUME	PLASTICS	MARBLE WASTE						
Overall	(0.383,0.417,0.915,0.951)	(0.366,0.829,0.829,0.887)	(0.392,0.449,0.676,0.723)	(0.476,0.5,0.949,0.97)	(0.437,0.473,0.817,0.871)	(0.348,0.396,0.635,0.457)	0.667	**0.728**	0.56	0.724	0.65	0.459
C1	(0.383,0.418,0.916,0.951)	(0.03,0.051,0.521,0.549)	(0.149,0.179,0.681,0.723)	(0.477,0.5,0.949,0.97)	(0.051,0.086,0.581,0.623)	(0.321,0.35,0.846,0.41)	0.667	0.288	0.433	**0.724**	0.335	0.482
C2	(0.314,0.37,0.782,0.838)	(0.108,0.16,0.54,0.591)	(0.174,0.233,0.628,0.688)	(0.388,0.439,0.84,0.893)	(0.221,0.276,0.678,0.737)	(0.311,0.363,0.768,0.433)	0.576	0.35	0.431	**0.64**	0.478	0.469
C3	(0.268,0.321,0.77,0.818)	(0.08,0.12,0.532,0.568)	(0.139,0.192,0.62,0.669)	(0.405,0.453,0.88,0.92)	(0.188,0.243,0.685,0.735)	(0.309,0.353,0.802,0.429)	0.544	0.325	0.405	**0.665**	0.463	0.473
C4	(0.317,0.368,0.641,0.683)	(0.292,0.331,0.601,0.64)	(0.388,0.445,0.726,0.767)	(0.233,0.274,0.528,0.566)	(0.267,0.324,0.603,0.647)	(0.263,0.317,0.589,0.367)	0.502	0.466	**0.581**	0.4	0.46	0.384
C5	(0.101,0.146,0.567,0.618)	(0.403,0.451,0.878,0.923)	(0.079,0.128,0.548,0.6)	(0.14,0.199,0.643,0.699)	(0.334,0.388,0.84,0.891)	(0.078,0.122,0.545,0.174)	0.358	**0.664**	0.339	0.42	0.613	0.23
C6	(0.376,0.422,0.612,0.666)	(0.292,0.343,0.547,0.598)	(0.403,0.455,0.657,0.708)	(0.412,0.445,0.627,0.673)	(0.385,0.43,0.625,0.673)	(0.362,0.413,0.62,0.468)	0.519	0.445	**0.556**	0.539	0.528	0.466
C7	(0.201,0.248,0.563,0.628)	(0.313,0.346,0.658,0.718)	(0.268,0.308,0.62,0.682)	(0.325,0.363,0.657,0.714)	(0.452,0.482,0.752,0.799)	(0.332,0.37,0.665,0.423)	0.41	0.509	0.469	0.515	**0.621**	0.447

marks. Rice husk can be used both natural and combustion yield. In addition, another type of mix style natural and grinded. However, best results can be obtained with combusted rice husk ash and grinded. Because, fineness of binder material is one of the most important property for concrete to adhere materials each other. Plastics and pet bottles are 4th material with 0.65 points. Generally, plastic materials could not use in concrete directly; these materials should be grinded or should be shredded like chips. This mechanical workmanship is negative for processing. General plastics and pet bottles contribute workability but compressive and flexural strength contributions come to more important role than other properties. This material cannot supply enough contribution in terms of compressive and flexural strength. For this reason, general plastics and pet bottles locate 4rd order in the list. Demolition waste is 5th material with 0.56 numeric ranking. Demolition waste is a completely realistic example of recycling of material. Accessibility of this material depends on the developing of the country. Water absorption of this material rather high while compared others due to the dust of demolished materials. According to studies (Akçaözü *et al*. 2010, Silva *et al*. 2005, Albano *et al*. 2009, Frigione 2010) replacement ratio is inversely proportional with a few important parameters like compressive strength and flexural strength. Experimental results also depend mostly on the size of replaced materials. For instance, if replaced material is composed of fine recycled aggregate, this replacement has more contribution than coarse recycled aggregate. However, both size have not so much effect than natural aggregate. These effects locate this material at 5th number in this study. Final material is marble dust with 0.459 points. This material is studied as cement, sand and aggregate in concrete. Waste marble has no considerable effect on concrete in terms of strength when used as aggregate by Frigione (2010). To obtain normal workability condition, plasticizer has to be added with waste marble aggregate to concrete mix according to Rao *et al*. (2007). Waste marble powder is used mostly in self compacting concrete (SCC) according to previous studies (Evangelista *et al*. 2014, Chan *et al*. 2006, Wagih *et al*. 2013, Andre *et al*. 2014). Waste marble powder gives satisfied results in SCC on behalf of V-funnel, L-500 tests related to self-compacting parameters. However, these contributions have not positive effect on the ordinary concrete. Due to these negative effects, Waste marble dust is located last line in the ranking order.

5. Conclusions

In this paper, optimum waste material selection is proposed for construction industry. A Choquet integral based fuzzy approach is used. The proposed approach has novelty for MCDM method for the problems having interactive criteria under fuzziness in construction industry. The selection is very important issue for civil engineering application. Because, many buildings have started to produce with waste materials especially Europe and other developed countries. The recycling process is indispensable in order not to consume all natural resources due to increasing population day by day. The uncontrolled logarithmic increase is forced scientists to look for alternative materials to produce daily life facilities. This paper clarifies which material is more suitable in terms of many engineering properties. Considered engineering properties are compressive strength, flexural strength, workability, accessibility, toughness, tensile strength, water absorption and compactness. Results of this study are listed below;

- Waste tyre is selected as suitable material.
- Silica fume is ranked as second more suitable material which has slight distinction results.
- According to the Choquet integral based fuzzy approach results, there is a small difference between waste tyre and silica fume.
- This small difference proves that these two materials can be use according to their production purposes.
- Waste tyre can be selected specially to resist dynamic activity due to high toughness ratio. Silica fume does not have this property. For this reason, it can be used for the rest of the purpose particularly high strength concrete productions.

The proposed model can give an insight for evaluating waste materials for construction industry. Sewage sludge, foam, sugar cane, paint and foundry sand can be considered as different waste materials for future studies. In addition, social, environmental, transportation and disposal cost criteria can be also taken into account in waste material selection process. Other fuzzy multi-criteria decision making methods such as the VlseKriterijumska Optimizacija I Kompromisno Resenje (VIKOR), ANP, Decision Making Trial and Evaluation Laboratory (DEMATEL) and Elimination et choix traduisant la realité (ELECTRE) based on fuzzy sets can be used for evaluating waste materials for construction industry.

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